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Recent changes in global drylands: Evidences from two major aridity databases

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ABSTRACT

Drying of terrestrial areas is a critical issue in our era of climate change. However, there is limited knowledge on the current spatial status of drylands, which can be assessed using updated and more rigorous data than information used in the initial dryland estimations. Here we investigate the current extent of drylands globally, continentally and nationally by analysing one of the most recent aridity database (1950–2000 period) and compare statistically, for the first time, with the initial dryland estimations (1951–1980). Using diachronic analysis between the databases, we found that drylands are currently almost 4% larger worldwide than expected and cover 45.4% of the Earth's land surface. This net increase of global dryland areas is due to the expansion of arid (+3.4%) and semi-arid (+0.9%) areas, whilst hyper-arid zones decreased (−0.8%) and dry sub-humid areas remained stable. Except for Europe and South America, all continents have experienced a net expansion of arid environments in the recent climate database. Our findings show that Asia is home to the world's largest increases in dryland areas, where China alone accounts for almost one third of the new lands exposed to aridity worldwide. The Earth's drier conditions can generally be attributed to climate changes occurring after 1980. Our results highlight large-scale drying processes and therefore the exacerbation of land degradative conditions at low and middle latitudes. Also, our findings signal the danger of triggering certain positive feedbacks in global warming, considering the newly-identified drylands migration towards higher latitudes in North America and Asia, which can modify the albedo and destabilize the large carbon pools in permafrost, peatlands or boreal forests.

1. Introduction

One of the main environmental implications of climate change is the drying of extensive global areas (Feng and Fu, 2013; Fu and Feng, 2014; Sherwood and Fu, 2014; Huang et al., 2016; Prăvălie, 2016; Cheval et al., 2017), which challenges for many United Nations sustainable development goals, such as eradicating poverty, ending hunger, ensuring human well-being or combating desertification (United Nations, 2015). On a multiannual temporal scale, dryness is specific to dryland systems, which are critical environments with a humidity deficit below 0.65 mm/mm (Middleton and Thomas, 1997; Middleton and Sternberg, 2013). This ratio between precipitation (P) and potential evapotranspiration (PET) defines the Aridity Index (AI), which is the most widely used statistical instrument for the analysis of global aridity (Middleton and Thomas, 1997; Trabucco and Zomer, 2009; Middleton and Sternberg, 2013; Lin et al., 2015; Prăvălie, 2016). The index clearly delimits four types of drylands – dry sub-humid (DSH, AI between 0.65 and 0.5 mm/mm), semi-arid (SA, 0.5–0.2 mm/mm), arid (A, 0.2–0.05 mm/mm) and hyper-arid (HA, < 0.05 mm/mm) land systems. These systems with low water availability are less thoroughly studied compared to other terrestrial systems (e.g. tropical environments), because they are often considered to be less complex (given their low biodiversity, for instance), and therefore less important (Schimel, 2010). However, with the multiple global-scale implications (both positive and negative) of drylands, this state of affairs is unjustified.

Firstly, drylands are considered Earth's largest biome – previous estimates indicate they cover 41% (~61 mil km^2) of the total global land area (Safriel et al., 2005). This vast biome features a rich biodiversity (e.g. ~20% of major global plant diversity hotspots), which enhances the multifunctionality of these environments, e.g. primary productivity, carbon (C) storage and nutrient cycles (Maestre et al., 2012). Secondly, global drylands host > 2 billion people, mostly in

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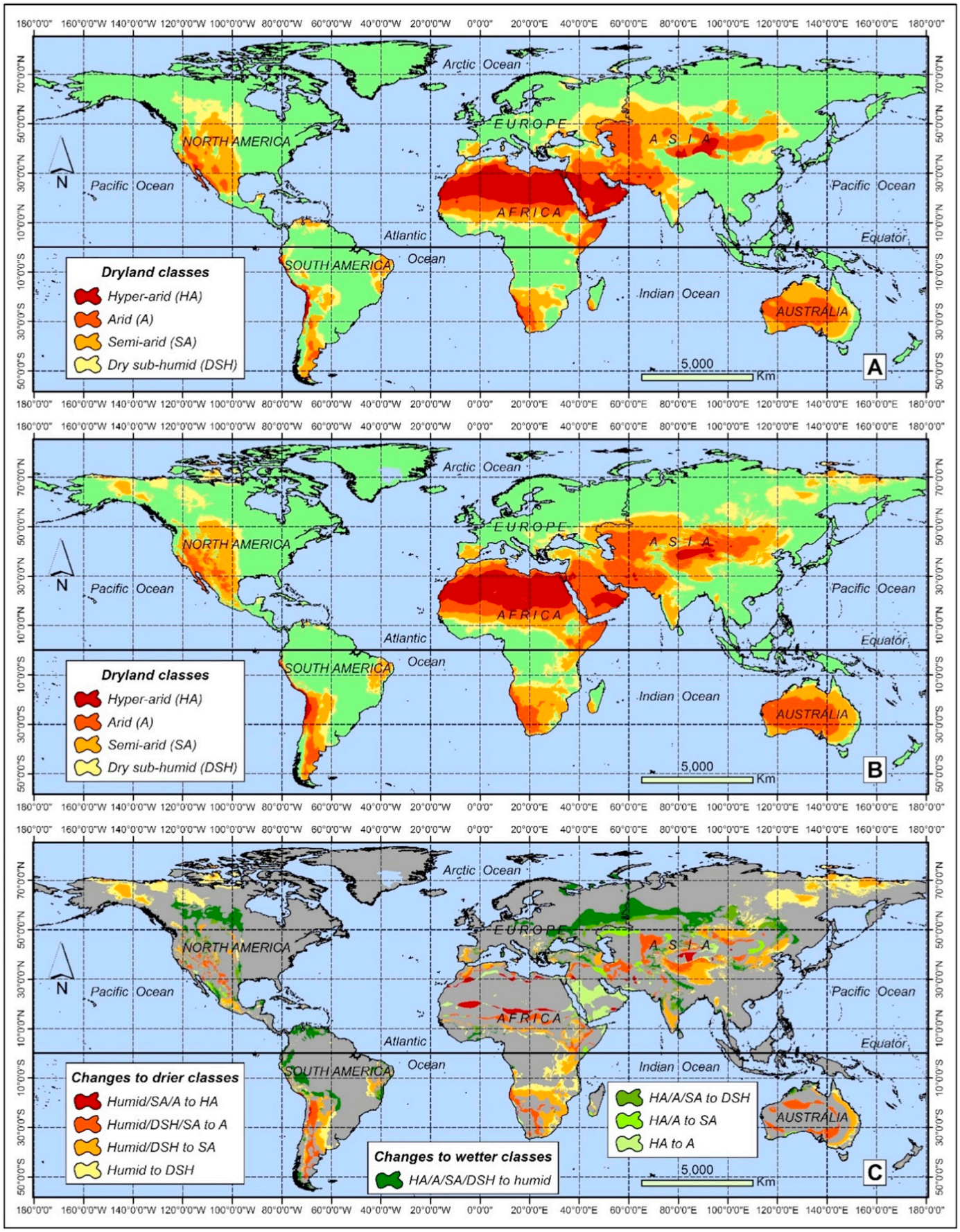

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Fig. 1. Previous estimates (a) of the Earth's drylands (spatial data processed after Middleton and Thomas, 1997) versus current estimates (b), based on a new global AI database (data processed after Trabucco and Zomer, 2009) and spatial differences between these two databases (c). Note: in maps a and b, light green reveals humid areas, while in map c gray shows areas without changes; in the case of changes to drier classes, the only transition that was not identified on the entire global scale was that from DSH to HA systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

developing countries (Middleton et al., 2011). The majority live in developing countries (> 1 billion) and are affected by poverty, primarily due to environmental change, social factors and large-scale desertification (Middleton et al., 2011). Severe forms of this degradation process affect the biological productivity of lands and are recorded in 10–20% of these arid environments (Reynolds et al., 2007). Thirdly, drylands have a discreet (indirect) importance, in various ways, for other global systems, such as the atmosphere, which can be cooled by reducing the incoming solar radiation, amid dust aerosol enhancement (Zhao et al., 2015). Another example consists of providing essential nutrients (e.g. phosphorus and iron), by means of wind dispersion, to terrestrial (Amazon forests) or marine (Atlantic phytoplankton or Caribbean coral reefs) ecosystems that are thousands of km away from the main dust sources, e.g. the Bodélé Depression (Chad) that emits ~50% of the mineral aerosols of the Sahara (Washington et al., 2009).

These characteristics become more important as drylands expand due to global warming, which has accelerated starting with ~1980 (Diffenbaugh and Field, 2013; IPCC, 2013). Therefore, we hypothesized that with updated and more rigorous climate data analysis drylands could in fact be larger than initially estimated based on climate data recorded until 1980 (Middleton and Thomas, 1997). To test this hypothesis, we analyzed the current extent of dryland areas by comparing one of the most current available global AI (obtained from CGIAR global climate database, which covers the 1950–2000 period) (Trabucco and Zomer, 2009) to the initial global AI (1951–1980) (Middleton and Thomas, 1997). For this we used representative geostatistical tools and methods to spatially analyze the four types of drylands from the two databases simultaneously.

To the best of our knowledge, this is the first study to analyze the spatial and temporal dynamics of arid environments on global, continental and national scales, using two climatic databases, which are based on two global aridity indices. Unlike a previous study that approached statistical analyses only on the current AI (which corresponds to the new aridity database, used in this study) (Prăvălie, 2016), the present research features a concrete diachronic analysis between the new AI and the previous AI (or the initial aridity database, also used in this paper), and also signals the statistical differences between the two global climatic indices. Therefore, even though the new AI is a common database investigated both in the previous paper and our work, the detailed statistical analysis of the previous AI and especially of the differences between the two aridity databases (in terms of net changes in drylands area, and especially in terms of mapping dryland system transitions after 1980) are results obtained for the first time in this paper.

Essentially, our approach aims to deliver new results on the recent changes in dryland expansion across the globe, based on a detailed comparative analysis of initial and current global database. Although the current climatic database is only updated up to the year 2000, it is deemed recent and representative for this paper's objective, considering it covers the extensive interval 1950–2000 (aridity databases that cover periods of more than five decades are rare/non-existent at global scale, at least to the best of our knowledge) and is the only freely-available global high-resolution aridity database, as far as we are aware. Moreover, the reliability of the current aridity data used in this study is also validated by the fact that this geo-database has already been used successfully in other recent/relatively recent global studies (Prăvălie, 2016; Plaza et al., 2018) that focused on the assessment of various environmental issues associated to the current extent of dryland systems.

2. Data and methods

In order to test our hypothesis of a more arid world than previously acknowledged, we first downloaded the global raster data for aridity zones, both the ones initially developed by UNEP in early 1990 (online data source: https://www.unep-wcmc.org/resources-and-data#data) (Middleton and Thomas, 1997), and the ones developed in 2009 by CGIAR (Consultative Group for International Agricultural Research) Consortium for Spatial Information (online data purchased at http://www.cgiar-csi.org/data/global-aridity-and-pet-database) (Trabucco and Zomer, 2009). The latter can be considered current, seeing as they are based on a climatic dataset that covers the period 1950–2000, compared to the older shorter period 1951–1980, used for the initial drylands extent. We subsequently classified the two aridity databases (expressed as two aridity indices) in four classes, based on the established intervals 0.65–0.5 mm/mm (DSH), 0.5–0.2 mm/mm (SA), 0.2–0.05 mm/mm (A) and < 0.05 mm/mm (HA), for the initial AI (Middleton and Thomas, 1997), and 0.65–0.5 mm/mm (DSH), 0.5–0.2 mm/mm (SA), 0.2–0.03 mm/mm (A) and < 0.03 mm/mm (HA), for the new AI (Trabucco and Zomer, 2009).

The slightly different setting for classes A and HA was chosen in accordance with methodological specifications described in specialized sources (Middleton and Thomas, 1997; Trabucco and Zomer, 2009). This was due to the fact that the Thornthwaite PET value assessment method (used for the initial drylands dataset) is considered to be inferior to the Hargreaves method (used for the more recent drylands dataset), given the fact that the former generally underestimates this climate parameter's values in highly arid regions (Prăvălie, 2016). As a result, HA areas were adjusted upward to 0.05 in the initial database (Middleton and Thomas, 1997), as opposed to the 0.03 threshold used in the recent database (Trabucco and Zomer, 2009).

In order to compare the two spatial databases as uniformly as possible, we deemed it necessary to lightly intervene in the initial drylands data by including certain mask lake areas (large lake areas that were not included in any aridity class although they were surrounded by dryland systems) in the adjacent aridity zones. We believe the correction was necessary because the lake areas that were not included in any of the four arid climate types would have increased the area differences between the initial and the new AI classes, as in the latter there are no such spatial gaps. For instance, the Aral Sea (Asia) area was included in the arid climate class, as it was completely surrounded by this aridity class. Other similar examples include Nasser Lake in Africa (included in HA class), Sobradinho Lake in South America (SA class) and Eyre Lake in Australia (A class). In order to accurately detect the lake areas that correspond to certain aridity areas in the initial drylands data, we used polygonal areas of global lakes, available at http://www.naturalearthdata.com/downloads/10m-physical-vectors. However, the final difference between the original and the corrected initial data was insignificant, i.e. 185,595.7 km^2, which represents only 0.3% of the original drylands area. Therefore, this data correction procedure is the main reason why our reassessed data of the initial drylands cover is slightly different (more extensive areas) compared to the original data briefly presented (on a global or at most continental scale) in the official reports (Middleton and Thomas, 1997; Safriel et al., 2005).

The spatial analysis was performed with the ArcGIS 10.1 software (www.esri.com). The two raster datasets, representing the initial and current extents of global drylands, were purchased with latitude and longitude coordinates with WGS 1984 as reference ellipsoid. After projecting them in a Mollweide projection with the same reference ellipsoid, we obtained a resolution of 1045.780 m for the initial drylands

Table 1
Drylands and humid areas extent in absolute and relative values at global and continental level – initial drylands area/current drylands area/difference between the initial and current dryland areas.

	No.	Spatial unit	Drylands/humid area (km^2/% of the global/continental area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km^2)[a]	(%)[b]	(km^2)[a]	(%)[b]	(km^2)[a]	(%)[b]	(km^2)[a]	(%)[b]	(km^2)[a]	(%)[b]	(km^2)[a]	(%)[b]
Initial drylands (D1)	1.	Globe	9,825,705.2	6.7	15,835,353.5	10.8	22,760,264.3	15.5	13,154,261.5	8.9	61,575,584.5	41.9	85,469,535.6	58.1
	2.	N & C America	26,650.2	0.1	845,197.3	3.5	3,926,337.9	16.2	2,188,543.1	9.0	6,986,728.6	28.8	17,262,840.0	71.2
	3.	South America	251,816.6	1.4	436,559.2	2.5	2,559,080.4	14.4	2,110,052.5	11.9	5,357,508.7	30.1	12,437,603.8	69.9
	4.	Europe	0.0	0.0	37,806.6	0.4	1,015,991.5	10.3	1,885,210.9	19.1	2,939,009.0	29.8	6,924,142.4	70.2
	5.	Africa	6,769,239.7	22.5	5,043,385.4	16.8	5,119,243.6	17.0	2,815,199.5	9.4	19,747,068.2	65.7	10,321,576.7	34.3
	6.	Asia	2,777,998.7	6.2	6,428,542.8	14.4	7,037,930.3	15.8	3,552,753.7	8.0	19,797,225.5	44.4	24,837,415.5	55.6
	7.	Australia & Oceania	0.0	0.0	3,043,862.2	37.4	3,101,680.6	38.1	602,501.9	7.4	6,748,044.6	82.9	1,392,198.1	17.1
Current drylands (D2)	1.	Globe	8,619,329.6	5.9	20,847,849.9	14.2	24,082,933.7	16.4	13,193,688.3	9.0	66,743,802.2	45.4	80,301,317.9	54.6
	2.	N & C America	4395.7	0.0	1,080,374.2	4.5	3,956,998.6	16.3	2,520,112.4	10.4	7,561,880.8	31.2	16,687,687.8	68.8
	3.	South America	262,808.7	1.5	1,053,170.4	5.9	2,409,942.6	13.5	1,381,657.1	7.8	5,107,579.2	28.7	12,687,533.3	71.3
	4.	Europe	0.0	0.0	5210.3	0.1	791,203.1	8.0	937,713.4	9.5	1,734,126.7	17.6	8,129,024.7	82.4
	5.	Africa	7,027,649.4	23.4	5,896,781.2	19.6	6,526,707.3	21.7	3,092,495.9	10.3	22,543,634.1	75.0	7,525,010.8	25.0
	6.	Asia	1,324,475.8	3.0	8,897,567.2	19.9	7,711,447.7	17.3	4,829,873.0	10.8	22,763,363.9	51.0	21,871,277.1	49.0
	7.	Australia & Oceania	0.0	0.0	3,914,746.6	48.1	2,686,634.4	33.0	431,836.5	5.3	7,033,217.5	86.4	1,107,025.2	13.6
Differences D2-D1	1.	Globe	−1,206,375.6	−0.8	+5,012,496.4	+3.4	+1,322,669.4	+0.9	+39,426.8	+0.0	+5,168,217.7	+3.5	−5,168,217.7	−3.5
	2.	N&C America	−22,254.5	−0.1	+235,176.9	+1.0	+30,660.7	+0.1	+331,569.3	+1.4	+575,152.2	+2.4	−575,152.2	−2.4
	3.	South America	+10,992.1	+0.1	+616,611.2	+3.5	−149,137.8	−0.8	−728,395.4	−4.1	−249,929.5	−1.4	+249,929.5	+1.4
	4.	Europe	0.0	0.0	−32,596.3	−0.3	−224,788.4	−2.3	−947,497.5	−9.6	−1,204,882.3	−12.2	+1,204,882.3	+12.2
	5.	Africa	+258,409.7	+0.9	+853,395.8	+2.8	+1,407,463.7	+4.7	+277,296.4	+0.9	+2,796,565.9	+9.3	−2,796,565.9	−9.3
	6.	Asia	−1,453,522.9	−3.3	+2,469,024.4	+5.5	+673,517.4	+1.5	+1,277,119.3	+2.9	+2,966,138.4	+6.6	−2,966,138.4	−6.6
	7.	Australia & Oceania	0.0	0.0	+870,884.4	+10.7	−415,046.2	−5.1	−170,665.4	−2.1	+285,172.9	+3.5	−285,172.9	−3.5

Note: Abbreviations: N&C America – North and Central America; Differences D2-D1 – differences between D2 and D1 (positive/negative values indicate larger/smaller surfaces of drylands in the current database compared with the initial database); in the case of percentage-based differences, certain possible minor inconsistencies of results obtained from differences D2-D1 are due to values with a single decimal point (the differences were obtained based on more detailed percentage values, with four decimal points, which were not included in this table).

[a] Absolute values of drylands area.

[b] Percentage of absolute drylands area in relation to the global/continental area.

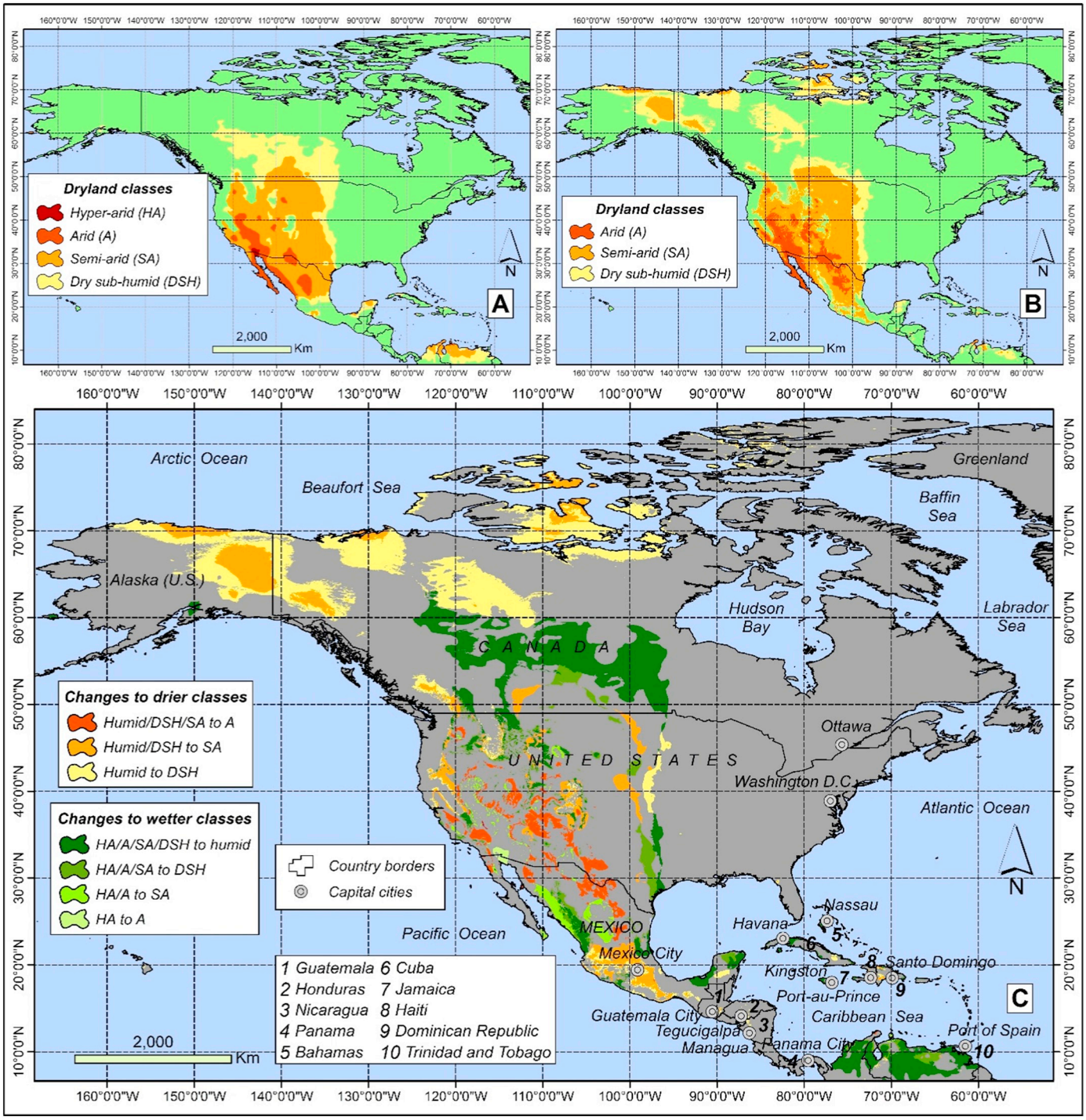


Fig. 2. Previous estimates (a) of the North and Central America drylands (spatial data processed after Middleton and Thomas, 1997) versus current estimates (b), based on a new global AI database (data processed after Trabucco and Zomer, 2009) and spatial differences between these two databases (c). Note: in maps a and b, light green reveals humid areas, while in map c gray shows areas without changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

raster, and a resolution of 858.838 m for the current drylands raster. We used the *Raster Calculator* module from the *Map Algebra* toolbox to resample the initial dryland raster to the same resolution as the current drylands raster (858.838 m) and to obtain an exact pixel per pixel superposition. In this manner, the geometry of the 2 raster datasets matched perfectly and therefore they became comparable.

After matching the geometry of the initial and current drylands rasters, we made further use of the *Zonal Histogram* module from the *Zonal* toolbox and the high spatial resolution vector polygons for the global/continental (made available at http://www.naturalearthdata.com/downloads/10m-physical-vectors) and national (http://www.gadm.org) spatial units, in order to extract the number of pixels for each aridity class and for each spatial unit. The results were exported in Excel (https://products.office.com/excel) and the areas of each aridity class within each spatial unit were computed by multiplying the number of pixels by pixel area, along with the percentages of each aridity class of the total global/continental/national area. We then computed the differences between the absolute surface areas (in km^2) of

Table 2
Drylands and humid areas extent in absolute and relative values at state level in North and Central America – initial drylands area/current drylands area/difference between the initial and current dryland areas.

	No.[a]	Country	Drylands/humid area (km²/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]
Initial drylands (D1)	1.	Canada	0.0	0.0	0.0	0.0	270,887.7	2.7	1,317,594.5	13.2	1,588,482.3	16.0	8,356,499.3	84.0
	2.	USA	15,680.8	0.2	382,573.0	4.0	2,921,497.4	30.8	622,715.9	6.6	3,942,467.2	41.6	5,545,392.9	58.4
	3.	Mexico	10,969.4	0.6	462,624.3	23.6	728,147.7	37.1	204,565.1	10.4	1,406,306.5	71.7	554,481.2	28.3
	4.	Bahamas	0.0	0.0	0.0	0.0	0.0	0.0	4709.3	35.0	4709.3	35.0	8738.5	65.0
	5.	Cuba	0.0	0.0	0.0	0.0	2201.5	2.0	26,404.1	23.7	28,605.7	25.7	82,668.4	74.3
	6.	Haiti	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27,219.3	100.0
	7.	Dom. Rep.	0.0	0.0	0.0	0.0	1531.1	3.2	4846.0	10.0	6377.1	13.2	41,984.7	86.8
	8.	Jamaica	0.0	0.0	0.0	0.0	1755.3	15.9	2873.0	26.0	4628.4	41.8	6431.4	58.2
	9.	Guatemala	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	109,781.1	100.0
	10.	Honduras	0.0	0.0	0.0	0.0	0.0	0.0	3778.6	3.3	3778.6	3.3	109,168.8	96.7
	11.	Nicaragua	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	128,998.1	100.0
	12.	Panama	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75,587.7	100.0
	13.	T-T	0.0	0.0	0.0	0.0	317.2	6.1	1056.5	20.3	1373.6	26.5	3818.0	73.5
Current drylands (D2)	1.	Canada	0.0	0.0	0.0	0.0	367,497.9	3.7	1,371,744.1	13.8	1,739,241.9	17.5	8,205,739.7	82.5
	2.	USA	2114.0	0.0	649,472.8	6.8	2,774,470.3	29.2	851,065.9	9.0	4,277,123.0	45.1	5,210,737.1	54.9
	3.	Mexico	2281.7	0.1	430,901.4	22.0	805,744.9	41.1	266,888.5	13.6	1,505,816.5	76.8	454,971.2	23.2
	4.	Bahamas	0.0	0.0	0.0	0.0	1137.9	8.5	2464.7	18.3	3602.6	26.8	9845.2	73.2
	5.	Cuba	0.0	0.0	0.0	0.0	86.4	0.1	7481.8	6.7	7568.2	6.8	103,705.9	93.2
	6.	Haiti	0.0	0.0	0.0	0.0	1357.9	5.0	2195.1	8.1	3552.9	13.1	23,666.4	86.9
	7.	Dom. Rep.	0.0	0.0	0.0	0.0	4547.6	9.4	6361.2	13.2	10,908.9	22.6	37,452.9	77.4
	8.	Jamaica	0.0	0.0	0.0	0.0	0.0	0.0	162.7	1.5	162.7	1.5	10,897.1	98.5
	9.	Guatemala	0.0	0.0	0.0	0.0	1279.0	1.2	2937.0	2.7	4216.0	3.8	105,565.1	96.2
	10.	Honduras	0.0	0.0	0.0	0.0	663.4	0.6	3856.7	3.4	4520.1	4.0	108,427.3	96.0
	11.	Nicaragua	0.0	0.0	0.0	0.0	213.3	0.2	4733.3	3.7	4946.6	3.8	124,051.5	96.2
	12.	Panama	0.0	0.0	0.0	0.0	0.0	0.0	221.4	0.3	221.4	0.3	75,366.3	99.7
	13.	T-T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5191.6	100.0
Differences D2-D1	1.	Canada	0.0	0.0	0.0	0.0	+96,610.2	+1.0	+54,149.6	+0.5	+150,759.6	+1.5	−150,759.6	−1.5
	2.	USA	−13,566.8	−0.1	+266,899.8	+2.8	−147,027.1	−1.5	+228,350.0	+2.4	+334,655.8	+3.5	−334,655.8	−3.5
	3.	Mexico	−8687.7	−0.4	−31,722.9	−1.6	+77,597.2	+4.0	+62,323.4	+3.2	+99,510.0	+5.1	−99,510.0	−5.1
	4.	Bahamas	0.0	0.0	0.0	0.0	+1137.9	+8.5	−2244.6	−16.7	−1106.7	−8.2	+1106.7	+8.2
	5.	Cuba	0.0	0.0	0.0	0.0	−2115.1	−1.9	−18,922.3	−17.0	−21,037.5	−18.9	+21,037.5	+18.9
	6.	Haiti	0.0	0.0	0.0	0.0	+1357.9	+5.0	+2195.1	+8.1	+3552.9	+13.1	−3552.9	−13.1
	7.	Dom. Rep.	0.0	0.0	0.0	0.0	+3016.5	+6.2	+1515.2	+3.1	+4531.8	+9.4	−4531.8	−9.4
	8.	Jamaica	0.0	0.0	0.0	0.0	−1755.3	−15.9	−2710.3	−24.5	−4465.7	−40.4	+4465.7	+40.4
	9.	Guatemala	0.0	0.0	0.0	0.0	+1279.0	+1.2	+2937.0	+2.7	+4216.0	+3.8	−4216.0	−3.8
	10.	Honduras	0.0	0.0	0.0	0.0	+663.4	+0.6	+78.1	+0.1	+741.5	+0.7	−741.5	−0.7
	11.	Nicaragua	0.0	0.0	0.0	0.0	+213.3	+0.2	+4733.3	+3.7	+4946.6	+3.8	−4946.6	−3.8
	12.	Panama	0.0	0.0	0.0	0.0	0.0	0.0	+221.4	+0.3	+221.4	+0.3	−221.4	−0.3
	13.	T-T	0.0	0.0	0.0	0.0	−317.2	−6.1	−1056.5	−20.3	−1373.6	−26.5	+1373.6	+26.5

Note: Country abbreviations: USA – United States of America, Dom. Rep. – Dominican Republic; T-T – Trinidad and Tobago; Differences D2-D1 – differences between D2 and D1 (positive/negative values indicate larger/smaller surfaces of drylands in the current database compared with the initial database); in the case of percentage-based differences, certain possible minor inconsistencies of results obtained from differences D2-D1 are due to values with a single decimal point (the differences were obtained based on more detailed percentage values, with four decimal points, which were not included in this table).

[a] The states are listed in a descending order considering the maximum latitude values of northern limits.

[b] Absolute values of drylands area.

[c] Percentage of absolute drylands area in relation to the state area.

current and initial drylands, as well as the differences between the percentages of the corresponding absolute surface areas.

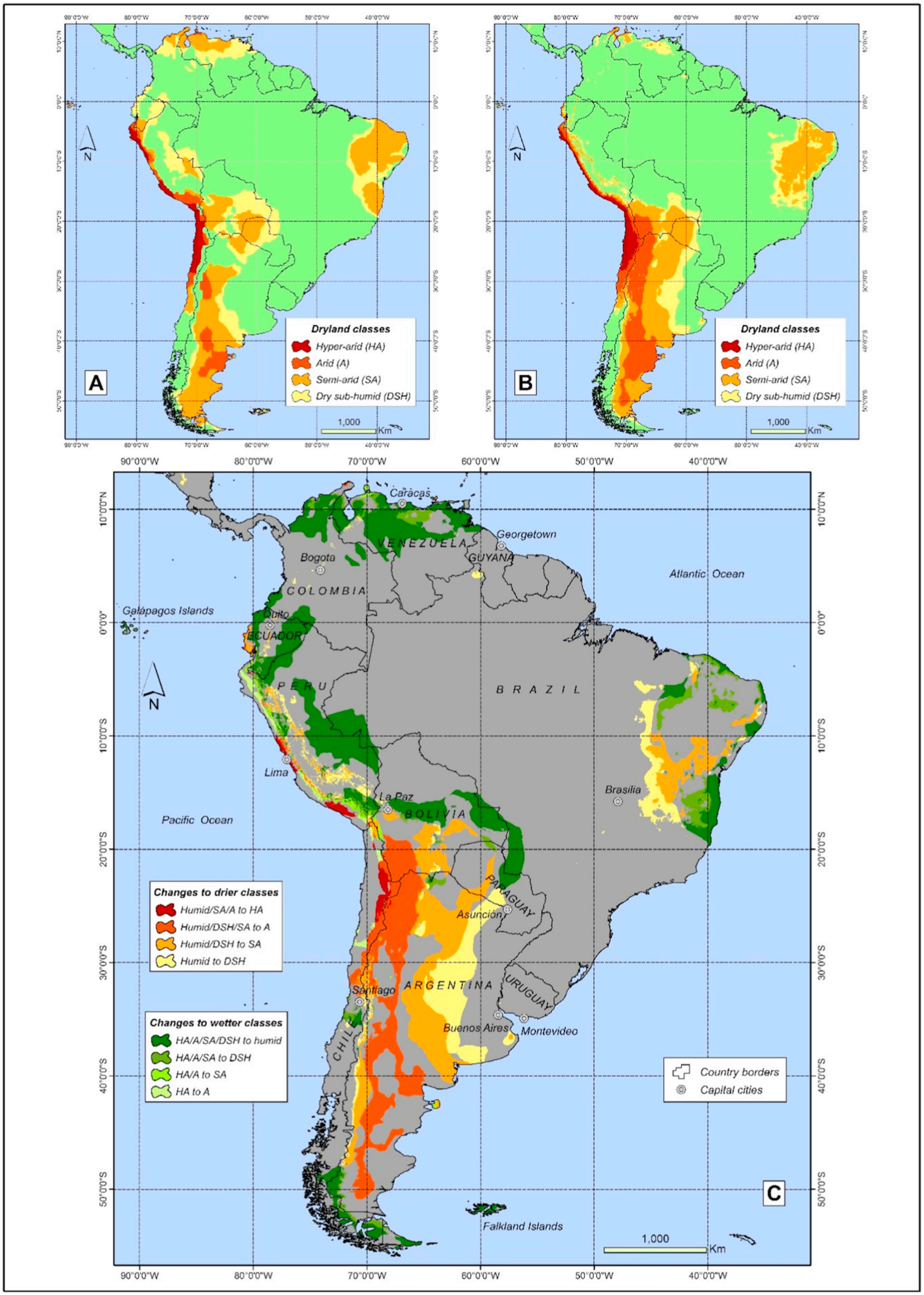
Also, for the purpose of mapping the transitions between the aridity classes for the two global climatic databases, we multiplied the initial drylands raster by 10 and then added the resulting raster to the current drylands raster, using the *Raster Calculator* ArcGIS software tool. Hence, we obtained a raster layer in which the pixel code represents the transitions between aridity classes by means of two-digit numbers – e.g. a pixel value of 21 is equivalent to a transition from arid (2) to hyper-arid (1) class. However, in order to synthesize transitions between dryland/humid classes, we finally decided to generalize the spatial information by grouping all dryland/humid classes exhibiting transitions towards drier classes or towards wetter classes, respectively (e.g. all inferior classes to the hyper-arid class, which in the new aridity database transitioned to the hyper-arid class, were grouped together; all dryland classes, which in the current aridity database transitioned to humid areas, were grouped together).

3. Results

3.1. Dryland changes in the global and continental contexts

We found that our planet is presently significantly more arid than previously estimated, both in terms of total area and intensity. New vast land exposed to aridity was identified in northwestern North America (Alaska), northeastern Asia (Siberia), and also at lower latitudes such as the central-southern region of Asia and eastern/southeastern Africa (Fig. 1). Also, extensive global regions experienced increased aridity that overwhelmingly outweigh the regions in which reduced aridity conditions were recorded (Fig. 1).

By comparing the quantitative area data extracted from the initial and current data sources, our statistical analyses highlight a total drylands expansion of 3.5% (> 5 mil km²) globally, with increases of up to 6.6% (~3 mil km²) in Asia and 9.3% (~2.8 mil km²) in Africa (Table 1). Overall, all continents, except for Europe (12.2%/~1.2 mil km²



(caption on next page)

Fig. 3. Previous estimates (a) of the South America drylands (spatial data processed after Middleton and Thomas, 1997) versus current estimates (b), based on a new global AI database (data processed after Trabucco and Zomer, 2009) and spatial differences between these two databases (c). Note: in maps a and b, light green reveals humid areas, while in map c gray shows areas without changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Drylands and humid areas extent in absolute and relative values at state level in South America – initial drylands area/current drylands area/difference between the initial and current dryland areas.

	No.[a]	Country	Drylands/humid area (km²/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]
Initial drylands (D1)	1.	Columbia	0.0	0.0	0.0	0.0	48,557.2	4.2	154,543.5	13.5	203,100.7	17.8	940,937.6	82.2
	2.	Venezuela	0.0	0.0	8340.2	0.9	191,943.3	20.9	254,701.6	27.7	454,985.1	49.6	463,101.4	50.4
	3.	Guyana	0.0	0.0	0.0	0.0	0.0	0.0	74.4	0.0	74.4	0.0	211,060.6	100.0
	4.	Brazil	0.0	0.0	0.0	0.0	804,720.0	9.4	504,907.2	5.9	1,309,627.3	15.3	7,242,255.0	84.7
	5.	Ecuador	0.0	0.0	2173.1	0.8	39,449.3	15.3	124,744.6	48.3	166,367.0	64.4	91,975.9	35.6
	6.	Peru	101,444.3	7.8	123,981.3	9.5	106,182.0	8.2	247,632.2	19.0	579,239.8	44.5	721,567.2	55.5
	7.	Bolivia	41.6	0.0	9112.3	0.8	271,334.0	24.9	349,425.4	32.1	629,913.3	57.8	459,547.2	42.2
	8.	Chile	150,330.7	19.8	50,883.5	6.7	83,353.0	11.0	28,273.2	3.7	312,840.4	41.2	446,156.2	58.8
	9.	Paraguay	0.0	0.0	0.0	0.0	134,713.3	33.6	86,601.2	21.6	221,314.5	55.1	180,123.5	44.9
	10.	Argentina	0.0	0.0	242,068.8	8.7	878,828.4	31.5	359,149.1	12.9	1,480,046.3	53.1	1,306,494.2	46.9
	11.	Uruguay	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	177,960.8	100.0
Current drylands (D2)	1.	Columbia	0.0	0.0	1555.5	0.1	11,618.8	1.0	20,611.2	1.8	33,785.6	3.0	1,110,252.7	97.0
	2.	Venezuela	0.0	0.0	125.4	0.0	36,022.0	3.9	106,404.6	11.6	142,552.1	15.5	775,534.4	84.5
	3.	Guyana	0.0	0.0	0.0	0.0	0.0	0.0	348.5	0.2	348.5	0.2	210,786.5	99.8
	4.	Brazil	0.0	0.0	0.0	0.0	727,133.3	8.5	468,972.8	5.5	1,196,106.1	14.0	7,355,776.2	86.0
	5.	Ecuador	0.0	0.0	2201.1	0.9	24,897.8	9.6	20,238.1	7.8	47,337.0	18.3	211,005.9	81.7
	6.	Peru	93,454.5	7.2	72,086.0	5.5	76,965.3	5.9	119,025.6	9.2	361,531.4	27.8	939,275.6	72.2
	7.	Bolivia	0.0	0.0	98,786.7	9.1	276,352.3	25.4	144,593.9	13.3	519,733.0	47.7	569,727.5	52.3
	8.	Chile	167,442.3	22.1	121,251.5	16.0	54,542.9	7.2	24,351.6	3.2	367,588.4	48.4	391,408.2	51.6
	9.	Paraguay	0.0	0.0	0.0	0.0	156,507.6	39.0	57,541.3	14.3	214,048.9	53.3	187,389.1	46.7
	10.	Argentina	1911.9	0.1	757,164.2	27.2	1,045,902.6	37.5	419,379.5	15.1	2,224,358.2	79.8	562,182.3	20.2
	11.	Uruguay	0.0	0.0	0.0	0.0	0.0	0.0	190.0	0.1	190.0	0.1	177,770.8	99.9
Differences D2-D1	1.	Columbia	0.0	0.0	+1555.5	+0.1	−36,938.4	−3.2	−133,932.3	−11.7	−169,315.1	−14.8	+169,315.1	+14.8
	2.	Venezuela	0.0	0.0	−8214.8	−0.9	−155,921.3	−17.0	−148,297.0	−16.2	−312,433.0	−34.0	+312,433.0	+34.0
	3.	Guyana	0.0	0.0	0.0	0.0	0.0	0.0	+274.1	+0.1	+274.1	+0.1	−274.1	−0.1
	4.	Brazil	0.0	0.0	0.0	0.0	−77,586.7	−0.9	−35,934.4	−0.4	−113,521.2	−1.3	+113,521.2	+1.3
	5.	Ecuador	0.0	0.0	+28.0	+0.0	−14,551.5	−5.6	−104,506.5	−40.5	−119,030.0	−46.1	+119,030.0	+46.1
	6.	Peru	−7989.8	−0.6	−51,895.3	−4.0	−29,216.7	−2.2	−128,606.6	−9.9	−217,708.4	−16.7	+217,708.4	+16.7
	7.	Bolivia	−41.6	0.0	+89,674.4	+8.2	+5018.3	+0.5	−204,831.5	−18.8	−110,180.3	−10.1	+110,180.3	+10.1
	8.	Chile	+17,111.6	+2.3	+70,368.0	+9.3	−28,810.1	−3.8	−3921.6	−0.5	+54,748.0	+7.2	−54,748.0	−7.2
	9.	Paraguay	0.0	0.0	0.0	0.0	+21,794.3	+5.4	−29,059.9	−7.2	−7265.6	−1.8	+7265.6	+1.8
	10.	Argentina	+1911.9	+0.1	+515,095.4	+18.5	+167,074.2	+6.0	+60,230.4	+2.2	+744,311.9	+26.7	−744,311.9	−26.7
	11.	Uruguay	0.0	0.0	0.0	0.0	0.0	0.0	+190.0	+0.1	+190.0	+0.1	−190.0	−0.1

Note: Differences D2-D1 – differences between D2 and D1 (positive/negative values indicate larger/smaller surfaces of drylands in the current database compared with the initial database); in the case of percentage-based differences, certain possible minor inconsistencies of results obtained from differences D2-D1 are due to values with a single decimal point (the differences were obtained based on more detailed percentage values, with four decimal points, which were not included in this table).

[a] The states are listed in a descending order considering the maximum latitude values of northern limits.

[b] Absolute values of drylands area.

[c] Percentage of absolute drylands area in relation to the state area.

increase of humid areas) and South America (1.4%/~250,000 km²), have experienced more intense aridity (Table 1). We therefore found that aridity currently affects 45.4% (almost 67 mil km²) of the Earth's terrestrial area, with notable differences in terms of the four aridity systems, i.e. 9% (13.2 mil km²), 16.4% (~24 mil km²), 14.2% (~21 mil km²) and 5.9% (8.6 mil km²) for DSH, SA, A and HA areas (Table 1). This is a significantly greater extent than previously estimated in the official reports (41.3% of the Earth's terrestrial area, or almost 61 mil km²) or our study's initial data reassessment (41.9%/almost 62 mil km², this value is slightly different due to the aridity data reprocessing, as previously mentioned in this paper).

Moreover, we also identified apparent global changes in the four dryland classes, i.e. increases for SA (0.9%, 1.3 mil km²) and A (3.4%, ~5 mil km²) systems, decreases for HA areas (with 0.8% or about 1.2 mil km²), and almost null changes for the DSH class (Table 1). Continentally, the greatest positive changes that resulted from the comparison of the two databases were found in Asia, for A (~2.5 mil km², which corresponds to 5.5% of the continent's area) and DSH (~1.3 mil km², ~3%) classes, and Africa, for SA (1.4 mil km², 4.7%) and HA (under 0.3 mil km²/1%) regions (Table 1). At the same time, certain notable decreases of the areas of the four types of arid environments were identified on all continents (peak values in Europe – for DSH and SA classes, Australia and Oceania – SA areas, and Asia – HA systems) except for Africa, which recorded an exclusive amplification of aridity conditions (Table 1).

3.2. Dryland changes in the national context

The diachronic analysis of the two datasets in North and Central America highlighted the amplest absolute expansions of total drylands in the United States (over 330,000 km²), Canada (~150,000 km²) and Mexico (~100,000 km²), and the most apparent changes in terms of percentages in Haiti, which exceeded the 13% threshold (Fig. 2, Table 2). These total changes are due to the expansion of DSH and SA

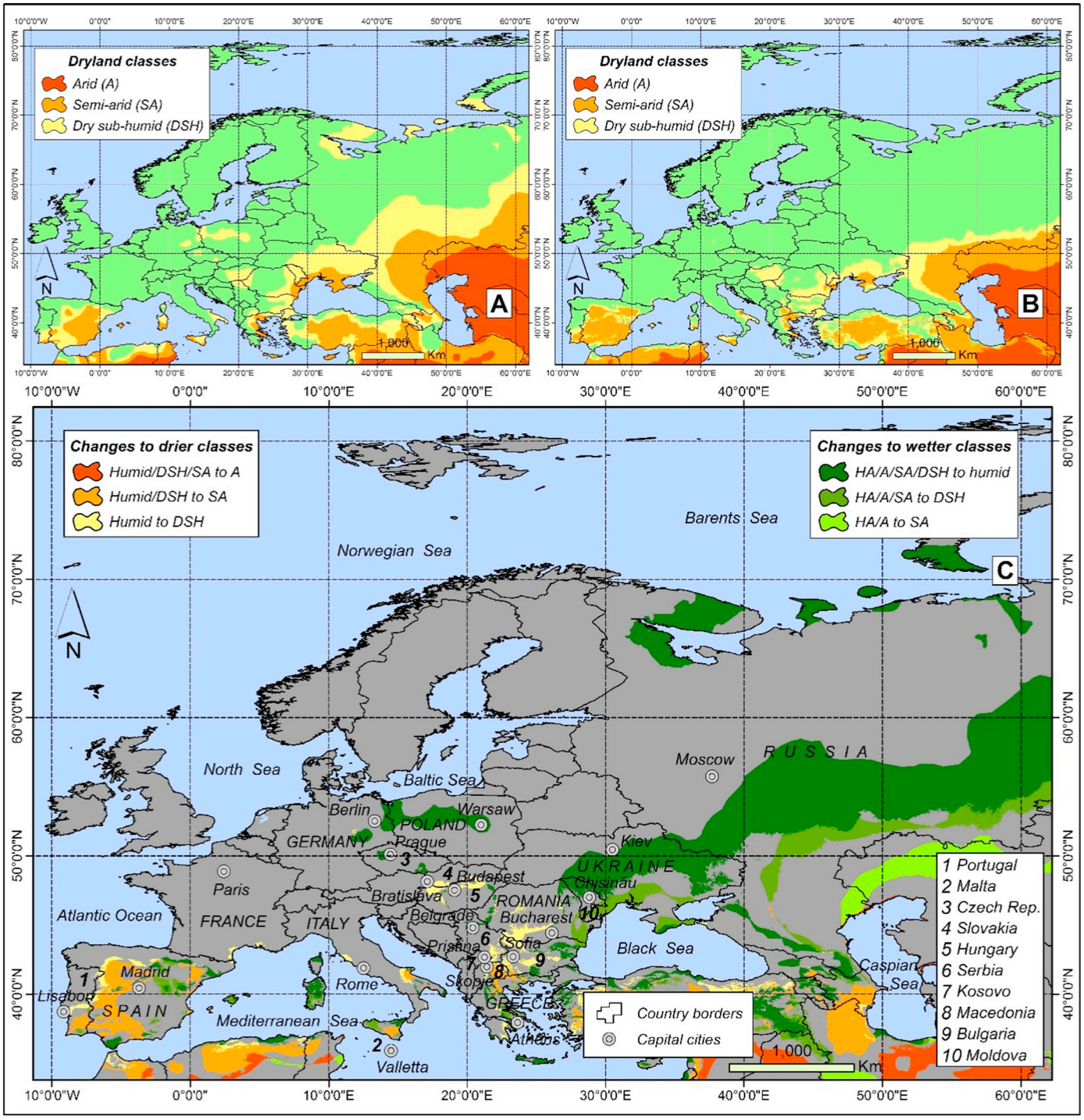


Fig. 4. Previous estimates (a) of the European drylands (spatial data processed after Middleton and Thomas, 1997) versus current estimates (b), based on a new global AI database (data processed after Trabucco and Zomer, 2009) and spatial differences between these two databases (c). Note: in maps a and b, light green reveals humid areas, while in map c gray shows areas without changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

regions in Canada and Mexico (with a magnitude of ~50,000–100,000 km^2), and of DSH and A areas in the United States (over 200,000 km^2 in both cases) (Fig. 2, Table 2). In contrast, several states in Central America experienced an improvement of aridity conditions, highest in Cuba, in terms of absolute values (net increase of humid areas of over 20,000 km^2), and in Jamaica, in terms of percentage (40%) (Table 2).

In South America there were massive transformations of aridity especially in Argentina, which recorded an enormous and uniform expansion of total drylands, equivalent to almost 750,000 km^2, or 27% of the national area (Fig. 3, Table 3). This expansion is due to an extent of ~70% to the increase of A areas (over 0.5 mil km^2) (Table 3). Also, Chile is another country with notable net increases in dryland areas (which exceed 50,000 km^2), but the remaining countries with a positive balance between the current and initial AI, Guyana and Uruguay, show insignificant changes (Table 3). The expansion of humid systems in the other seven countries is surprising, especially in Bolivia, Peru, Ecuador, Columbia and Venezuela (Fig. 3, Table 3), and generated net less aridity

Table 4
Drylands and humid areas extent in absolute and relative values at state level in Europe – initial drylands area/current drylands area/difference between the initial and current dryland areas.

	No.[a]	Country	Drylands/humid area (km^2/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]
Initial drylands (D1)	1.	Russia[b]	0.0	0.0	32,132.7	0.8	619,733.5	15.7	1,006,971.0	25.6	1,658,837.2	42.1	2,277,639.4	57.9
	2.	Germany	0.0	0.0	0.0	0.0	0.0	0.0	17,851.8	5.0	17,851.8	5.0	338,916.5	95.0
	3.	Poland	0.0	0.0	0.0	0.0	0.0	0.0	59,957.5	19.2	59,957.5	19.2	251,623.2	80.8
	4.	Ukraine	0.0	0.0	0.0	0.0	97,652.6	16.2	306,403.1	50.9	404,055.7	67.2	197,583.7	32.8
	5.	France	0.0	0.0	0.0	0.0	784.2	0.1	2888.3	0.5	3672.5	0.7	545,659.8	99.3
	6.	Czech Rep.	0.0	0.0	0.0	0.0	0.0	0.0	10,037.6	12.8	10,037.6	12.8	68,554.8	87.2
	7.	Slovakia	0.0	0.0	0.0	0.0	0.0	0.0	24.1	0.0	24.1	0.0	49,026.8	100.0
	8.	Hungary	0.0	0.0	0.0	0.0	0.0	0.0	42,980.7	46.3	42,980.7	46.3	49,901.1	53.7
	9.	Moldova	0.0	0.0	0.0	0.0	3967.8	11.7	29,799.9	88.2	33,767.7	99.9	28.8	0.1
	10.	Romania	0.0	0.0	0.0	0.0	20,981.8	8.8	72,369.4	30.5	93,351.2	39.3	144,037.9	60.7
	11.	Italy	0.0	0.0	0.0	0.0	22,881.5	7.6	45,268.6	15.0	68,150.1	22.6	232,771.0	77.4
	12.	Serbia	0.0	0.0	0.0	0.0	0.0	0.0	14,916.4	19.1	14,916.4	19.1	63,022.2	80.9
	13.	Bulgaria	0.0	0.0	0.0	0.0	3146.4	2.8	58,453.7	52.1	61,600.2	54.9	50,686.7	45.1
	14.	Spain	0.0	0.0	5673.9	1.1	198,265.7	39.1	155,457.8	30.7	359,397.4	70.9	147,225.5	29.1
	15.	Kosovo[c]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10,926.2	100.0
	16.	Macedonia	0.0	0.0	0.0	0.0	0.0	0.0	9214.1	37.1	9214.1	37.1	15,632.6	62.9
	17.	Portugal	0.0	0.0	0.0	0.0	6156.2	6.7	21,557.1	23.4	27,713.3	30.1	64,282.0	69.9
	18.	Greece	0.0	0.0	0.0	0.0	42,421.8	32.0	31,059.8	23.4	73,481.7	55.4	59,173.7	44.6
	19.	Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	326.0	100.0
Current drylands (D2)	1.	Russia[b]	0.0	0.0	2184.2	0.1	399,252.8	10.1	326,016.9	8.3	727,453.9	18.5	3,209,022.7	81.5
	2.	Germany	0.0	0.0	0.0	0.0	0.0	0.0	690.7	0.2	690.7	0.2	356,077.6	99.8
	3.	Poland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	311,580.7	100.0
	4.	Ukraine	0.0	0.0	0.0	0.0	36,554.5	6.1	154,519.1	25.7	191,073.6	31.8	410,565.8	68.2
	5.	France	0.0	0.0	0.0	0.0	0.0	0.0	4283.6	0.8	4283.6	0.8	545,048.7	99.2
	6.	Czech Rep.	0.0	0.0	0.0	0.0	0.0	0.0	2009.5	2.6	2009.5	2.6	76,582.9	97.4
	7.	Slovakia	0.0	0.0	0.0	0.0	0.0	0.0	4844.3	9.9	4844.3	9.9	44,206.6	90.1
	8.	Hungary	0.0	0.0	0.0	0.0	0.0	0.0	55,297.3	59.5	55,297.3	59.5	37,584.5	40.5
	9.	Moldova	0.0	0.0	0.0	0.0	94.8	0.3	16,016.6	47.4	16,111.4	47.7	17,685.1	52.3
	10.	Romania	0.0	0.0	0.0	0.0	8199.1	3.5	95,078.3	40.1	103,277.4	43.5	134,111.7	56.5
	11.	Italy	0.0	0.0	0.0	0.0	17,468.2	5.8	40,210.2	13.4	57,678.4	19.2	243,242.7	80.8
	12.	Serbia	0.0	0.0	0.0	0.0	0.9	0.0	19,822.3	25.4	19,823.2	25.4	58,115.4	74.6
	13.	Bulgaria	0.0	0.0	0.0	0.0	1256.4	1.1	63,590.5	56.6	64,846.9	57.8	47,440.0	42.2
	14.	Spain	0.0	0.0	3026.1	0.6	273,837.3	54.1	89,224.2	17.6	366,087.6	72.3	140,535.3	27.7
	15.	Kosovo[c]	0.0	0.0	0.0	0.0	0.0	0.0	639.5	5.9	639.5	5.9	10,286.7	94.1
	16.	Macedonia	0.0	0.0	0.0	0.0	7085.6	28.5	7506.7	30.2	14,592.3	58.7	10,254.4	41.3
	17.	Portugal	0.0	0.0	0.0	0.0	16,128.2	17.5	20,008.5	21.7	36,136.6	39.3	55,858.7	60.7
	18.	Greece	0.0	0.0	0.0	0.0	31,079.7	23.4	37,916.1	28.6	68,995.8	52.0	63,659.6	48.0
	19.	Malta	0.0	0.0	0.0	0.0	245.6	75.3	39.1	12.0	284.7	87.3	41.3	12.7
Differences D2-D1	1.	Russia[b]	0.0	0.0	−29,948.5	−0.8	−220,480.7	−5.6	−680,954.1	−17.3	−931,383.3	−23.7	+931,383.3	+23.7
	2.	Germany	0.0	0.0	0.0	0.0	0.0	0.0	−17,161.1	−4.8	−17,161.1	−4.8	+17,161.1	+4.8
	3.	Poland	0.0	0.0	0.0	0.0	0.0	0.0	−59,957.5	−19.2	−59,957.5	−19.2	+59,957.5	+19.2
	4.	Ukraine	0.0	0.0	0.0	0.0	−61,098.1	−10.2	−151,884.0	−25.2	−212,982.1	−35.4	+212,982.1	+35.4
	5.	France	0.0	0.0	0.0	0.0	−784.2	−0.1	+1395.3	+0.3	+611.1	+0.1	−611.1	−0.1
	6.	Czech Rep.	0.0	0.0	0.0	0.0	0.0	0.0	−8028.1	−10.2	−8028.1	−10.2	+8028.1	+10.2
	7.	Slovakia	0.0	0.0	0.0	0.0	0.0	0.0	+4820.2	+9.8	+4820.2	+9.8	−4820.2	−9.8
	8.	Hungary	0.0	0.0	0.0	0.0	0.0	0.0	+12,316.6	+13.3	+12,316.6	+13.3	−12,316.6	−13.3
	9.	Moldova	0.0	0.0	0.0	0.0	−3873.0	−11.5	−13,783.3	−40.8	−17,656.3	−52.2	+17,656.3	+52.2
	10.	Romania	0.0	0.0	0.0	0.0	−12,782.7	−5.4	+22,708.9	+9.6	+9926.2	+4.2	−9926.2	−4.2
	11.	Italy	0.0	0.0	0.0	0.0	−5413.3	−1.8	−5058.4	−1.7	−10,471.7	−3.5	+10,471.7	+3.5
	12.	Serbia	0.0	0.0	0.0	0.0	+0.9	+0.0	+4905.9	+6.3	+4906.8	+6.3	−4906.8	−6.3
	13.	Bulgaria	0.0	0.0	0.0	0.0	−1890.0	−1.7	+5136.8	+4.6	+3246.7	+2.9	−3246.7	−2.9
	14.	Spain	0.0	0.0	−2647.8	−0.5	+75,571.6	+14.9	−66,233.6	−13.1	+6690.2	+1.3	−6690.2	−1.3
	15.	Kosovo[c]	0.0	0.0	0.0	0.0	0.0	0.0	+639.5	+5.9	+639.5	+5.9	−639.5	−5.9
	16.	Macedonia	0.0	0.0	0.0	0.0	+7085.6	+28.5	−1707.4	−6.9	+5378.2	+21.6	−5378.2	−21.6
	17.	Portugal	0.0	0.0	0.0	0.0	+9972.0	+10.8	−1548.6	−1.7	+8423.3	+9.2	−8423.3	−9.2
	18.	Greece	0.0	0.0	0.0	0.0	−11,342.1	−8.6	+6856.3	+5.2	−4485.9	−3.4	+4485.9	+3.4
	19.	Malta	0.0	0.0	0.0	0.0	+245.6	+75.3	+39.1	+12.0	+284.7	+87.3	−284.7	−87.3

Note: Country abbreviations: Czech Rep. – Czech Republic; Differences D2-D1 – differences between D2 and D1 (positive/negative values indicate larger/smaller surfaces of drylands in the current database compared with the initial database); in the case of percentage-based differences, certain possible minor inconsistencies of results obtained from differences D2-D1 are due to values with a single decimal point (the differences were obtained based on more detailed percentage values, with four decimal points, which were not included in this table).

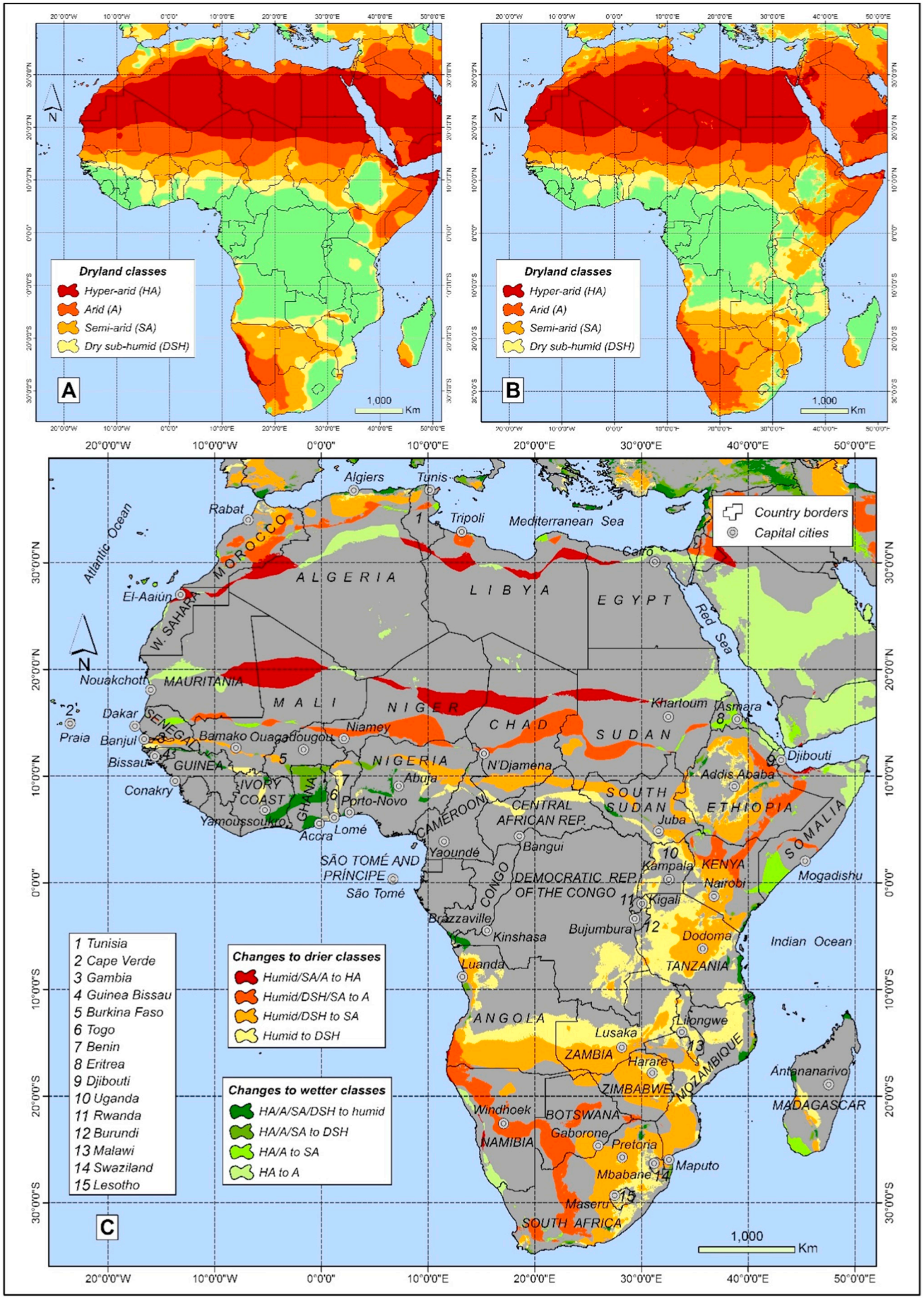
[a] The states are listed in a descending order considering the maximum latitude values of northern limits.

[b] Area of Russia in relation to the European continent.

[c] States with disputed sovereignty.

[d] Absolute values of drylands area.

[e] Percentage of absolute drylands area in relation to the state area.



(caption on next page)

Fig. 5. Previous estimates (a) of the African drylands (spatial data processed after Middleton and Thomas, 1997) versus current estimates (b), based on a new global AI database (data processed after Trabucco and Zomer, 2009) and spatial differences between these two databases (c). Note: in maps a and b, light green reveals humid areas, while in map c gray shows areas without changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

across national boundaries.

European countries experienced opposite changes in dryland areas, consequently, two groups of countries with different aridity dynamics can be delimited. The first category consists of a series of countries from the southern (Mediterranean) and central south-eastern regions of the continent, which recorded a lower water availability (Fig. 4) – across extensive areas especially in Romania and Hungary (net total drylands expansion of ~10,000 km^2 or over this threshold, exclusively due to the expansion of the DSH class), or with a higher intensity in Spain, where SA systems moved up in the new climate database by over 75,000 km^2 (15% of the national area) (Table 4). Also, according to our results, it appears that the expansion hotspots for arid environments (in terms of percentages) are found in Malta (87%) and Macedonia (22%) (Table 4).

The second category consists of several countries that recorded a higher water availability (mainly located in the continent's eastern region), as a result of the expansion of humid areas or of the transition of certain areas from drier to wetter classes. The epicentres of these major transformations include Russia (expansion of humid systems by almost 1 mil km^2, or about one quarter of European Russia), Ukraine (over 200,000 km^2, 35%) and, in part, Poland (~60,000 km^2, 19%) (Fig. 4, Table 4). These massive areas characterized by wetter conditions overwhelmingly counterbalanced the overall intensification of aridity in the Iberian, Italian and Balkan Peninsulas and in the continent's central south-eastern regions (Fig. 4), thus turning Europe in the global region with the amplest net positive changes in water availability.

In contrast, African countries experienced almost exclusive changes to drier conditions. Three major epicentres of these transformations can be noticed in the northern, eastern and southern regions of the continent, which is already the most arid in the world, considering that 75% of its total area is currently covered by drylands (Table 1). At the same time, a secondary hotspot for dryland changes was identified in the north (Morocco, Algeria and Libya), in the Mediterranean region (Fig. 5).

Our statistical analysis of the transition of arid environments in the first epicentre in the Saharan region indicated an ample net increase (even of over 150,000 km^2) of the most critical arid environments – HA systems, in large countries such as Mali, Niger, and Chad, and of A areas particularly in Sudan (Fig. 5, Table 5). The second hotspot in Eastern Africa consists of Ethiopia, Kenya and Tanzania, with expansions of generally less critical dryland classes, but also with impressive areas – records of over 250,000 km^2 for DSH and SA areas, and even over 500,000 km^2 for total drylands (peak continental expansion) in Tanzania (Fig. 5, Table 5). The third epicentre brings together several countries in Southern Africa with vast transitions to an apparent aridity – Angola (over 400,000 km^2 of new total drylands identified in the current aridity database, i.e. one third of the national area), Zambia (~370,000 km^2, 49%), South Africa (over 300,000 km^2, 25%), Mozambique (over 200,000 km^2, 29%) and Zimbabwe (over 100,000 km^2, 30%) (Fig. 5, Table 5). Also, while a vast and well-defined band with new arid conditions can be noticed in Namibia and Botswana (which continues in South Africa), the net advancement of total drylands in these two countries is almost null, considering the emergence of the new A class based on the transition generally from lower classes of aridity (Fig. 5, Table 5).

In Asia, the ~3 mil km^2 of new lands exposed to aridity (the amplest absolute expansion of drylands of all continents) are distributed across extensive areas in China (~1.6 mil km^2, 17%), Russia (almost 0.9 mil km^2, 7% of Asian Russia) and Mongolia (~0.5 mil km^2, 32%) (Fig. 6, Table 6). China alone, the country with the world's amplest net expansion of drylands by far, accounts for 55% of the new lands exposed to aridity in Asia, or 31% worldwide. In this instance, the expansion of arid environments is mostly to the increase of A and especially of SA areas, which totalled over 1 mil km^2 of new lands mainly in the country's south-western and north-eastern regions (Fig. 6, Table 6). Also, it is interesting to note that Russia has added a net total of almost 1 mil km^2 of new drylands, despite the simultaneous increase of humid systems (the amplest in Asia, according to cartographic observations) (Fig. 6, Table 6).

Certain considerable net expansions of total drylands (approximately between 50,000 and 70,000 km^2) occurred in three other Asian countries, namely Iran, Pakistan and Myanmar (Fig. 6, Table 6). In this instance, the analysis of statistical data grouped in different aridity classes indicated Iran as the most important aridity expansion hotspot, with a peak value for A systems (a difference of over 300,000 km^2 between the climate databases) (Table 6). Also, while our cartographic analyses showed some obvious changes to drier classes in other countries such as India and Kazakhstan (Fig. 6), the final net statistical results show that such changes were cancelled in these countries, in which the slightly larger increase of humid areas determined in fact an overall improvement of aridity conditions (Table 6).

Australia was also affected by an excessive aridity, considering the current expansion of total drylands of over 280,000 km^2 (4% of the total area), or three times larger for A zones (Table 7). Our results indicated a higher aridity degree for this continent-sized country in terms of intensity (approximately in the central-western region) and spatial coverage (expansion of arid environments mainly towards the east) (Fig. 7). We also noticed certain slight positive changes in dryland areas in Oceania, more significant in New Zealand (Fig. 7, Table 7).

4. Discussion

Since the first analyzed aridity database is based on climate data recorded between 1951 and 1980, and the second on data recorded from 1950 to 2000, it is likely that these spatial and statistical changes of arid environments are primarily due to the climate changes that occurred globally in the extended period of the new AI, 1981–2000. Therefore, we believe that the expansion of DSH and SA areas in northwestern North America and northeastern Asia is a projection of the accelerated climate warming recorded after 1980 which, coupled with decreasing P (IPCC, 2013), resulted in higher PET values in the P/PET ratio, and consequently in drier conditions. This reasoning was also confirmed by previous studies (Prăvălie, 2016), which, as already mentioned, compared the two climatic databases in a general manner (globally), without exploring the continental and especially national differences between these aridity databases. However, in addition to the differences in the longer climate data series used for obtaining the current AI, the almost 4% expansion of dryland systems is plausible considering also other important differences between the two databases.

These differences can be associated to a higher spatial resolution and a superior PET estimation method, used for obtaining the new global climate database (i.e. Hargreaves, which performs almost as well as the best FAO-PM method, compared to the previous Thornthwaite method, which underestimates this parameter's values) (Allen et al., 1998; Hargreaves and Allen, 2003; Trabucco and Zomer, 2009; Prăvălie, 2016). We also note the possible differences between the number of the weather stations used for the two climate databases, which could account for certain changes in the mapping of P and PET values and, as a result, in dryland coverage differences in certain parts of the world. However, we cannot clearly identify the importance of

Table 5
Drylands and humid areas extent in absolute and relative values at state level in Africa – initial drylands area/current drylands area/difference between the initial and current dryland areas.

	No.[a]	Country	Drylands/humid area (km²/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]
Initial drylands (D1)	1.	Tunisia	4923.6	3.2	102,174.8	65.8	34,706.1	22.4	11,523.9	7.4	153,328.4	98.8	1924.8	1.2
	2.	Algeria	1,778,110.3	76.8	295,748.7	12.8	112,374.3	4.9	70,087.0	3.0	2,256,320.3	97.4	60,340.5	2.6
	3.	Morocco	0.0	0.0	123,041.8	29.7	191,674.2	46.2	68,740.7	16.6	383,456.7	92.5	31,269.8	7.5
	4.	Libya	1,253,529.2	77.3	334,388.7	20.6	34,205.2	2.1	0.0	0.0	1,622,123.2	100.0	317.7	0.0
	5.	Egypt	915,470.2	92.7	69,445.0	7.0	158.6	0.0	0.0	0.0	985,073.8	99.7	2650.3	0.3
	6.	W. Sahara	226,667.9	84.4	41,257.1	15.4	0.0	0.0	0.0	0.0	267,925.0	99.8	568.3	0.2
	7.	Mauritania	569,470.2	54.4	455,023.4	43.5	21,080.2	2.0	0.0	0.0	1,045,573.8	99.9	875.3	0.1
	8.	Mali	238,669.7	19.0	645,178.5	51.3	261,055.8	20.8	101,015.6	8.0	1,245,919.6	99.1	11,202.5	0.9
	9.	Niger	450,326.1	37.8	498,218.4	41.9	241,551.5	20.3	0.0	0.0	1,190,096.1	100.0	53.8	0.0
	10.	Chad	396,521.5	31.0	365,133.6	28.6	357,842.2	28.0	148,575.4	11.6	1,268,072.7	99.3	9202.2	0.7
	11.	Sudan	709,421.0	37.7	616,995.0	32.8	519,846.6	27.6	36,224.1	1.9	1,882,486.7	100.0	396.5	0.0
	12.	Eritrea	18,875.4	15.7	89,182.2	74.0	10,718.9	8.9	0.0	0.0	118,776.6	98.5	1757.8	1.5
	13.	Cape Verde	375.1	9.1	1922.6	46.7	0.0	0.0	0.0	0.0	2297.8	55.8	1816.6	44.2
	14.	Senegal	0.0	0.0	52,861.9	26.8	90,140.3	45.7	43,951.9	22.3	186,954.0	94.7	10,458.9	5.3
	15.	Burkina Faso	0.0	0.0	7420.5	2.7	218,037.9	78.9	51,036.6	18.5	276,494.9	100.0	−11.8	0.0
	16.	Ethiopia	9450.3	0.8	208,243.1	18.3	278,993.9	24.5	170,197.0	15.0	666,884.3	58.6	471,380.5	41.4
	17.	Nigeria	0.0	0.0	18,276.1	2.0	248,928.2	27.2	265,358.2	29.0	532,562.5	58.3	381,216.8	41.7
	18.	Gambia	0.0	0.0	0.0	0.0	1460.0	13.6	9089.4	84.5	10,549.4	98.0	211.3	2.0
	19.	Cameroon	0.0	0.0	2870.8	0.6	33,350.0	7.1	25,174.9	5.4	61,395.7	13.1	407,705.3	86.9
	20.	Djibouti	4905.0	22.5	15,834.0	72.6	1005.1	4.6	0.0	0.0	21,744.1	99.7	75.9	0.3
	21.	Guinea-Bissau	0.0	0.0	0.0	0.0	0.0	0.0	2029.8	6.0	2029.8	6.0	31,989.2	94.0
	22.	Guinea	0.0	0.0	0.0	0.0	0.0	0.0	34,393.3	14.0	34,393.3	14.0	211,812.1	86.0
	23.	Benin	0.0	0.0	0.0	0.0	16,715.4	14.4	86,468.8	74.4	103,184.3	88.8	12,972.0	11.2
	24.	South Sudan	0.0	0.0	1750.9	0.3	307,236.5	48.3	198,741.4	31.3	507,728.9	79.8	128,161.4	20.2
	25.	Somalia	110,522.7	17.4	401,500.9	63.0	124,133.3	19.5	0.0	0.0	636,156.9	99.9	713.8	0.1
	26.	Ghana	0.0	0.0	0.0	0.0	54,889.5	22.9	106,167.8	44.3	161,057.3	67.1	78,808.9	32.9
	27.	Togo	0.0	0.0	0.0	0.0	5713.3	10.0	13,640.1	23.8	19,353.3	33.7	38,008.8	66.3
	28.	Central Afr. R.	0.0	0.0	0.0	0.0	22,275.6	3.6	103,640.3	16.6	125,915.9	20.2	498,296.9	79.8
	29.	Ivory Coast	0.0	0.0	0.0	0.0	0.0	0.0	122,981.7	38.0	122,981.7	38.0	200,737.1	62.0
	30.	D.R. of Congo	0.0	0.0	0.0	0.0	0.0	0.0	11,731.7	0.5	11,731.7	0.5	2,331,882.3	99.5
	31.	Kenya	0.0	0.0	130,419.6	22.3	207,618.6	35.5	80,310.5	13.7	418,348.7	71.4	167,309.9	28.6
	32.	Uganda	0.0	0.0	0.0	0.0	1357.2	0.6	5288.9	2.2	6646.1	2.7	236,403.3	97.3
	33.	R. of Congo	0.0	0.0	0.0	0.0	0.0	0.0	1231.5	0.4	1231.5	0.4	342,722.5	99.6
	34.	STP	0.0	0.0	0.0	0.0	811.5	80.4	0.0	0.0	811.5	80.4	197.5	19.6
	35.	Tanzania	0.0	0.0	0.0	0.0	0.0	0.0	96,812.6	10.2	96,812.6	10.2	851,118.2	89.8
	36.	Rwanda	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25,429.5	100.0
	37.	Burundi	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27,142.2	100.0
	38.	Angola	0.0	0.0	0.0	0.0	97,508.2	7.8	146,102.6	11.6	243,610.9	19.4	1,011,671.8	80.6
	39.	Zambia	0.0	0.0	0.0	0.0	5373.1	0.7	118,251.6	15.6	123,624.7	16.4	632,183.8	83.6
	40.	Malawi	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	118,718.0	100.0
	41.	Mozambique	0.0	0.0	0.0	0.0	70,604.3	8.9	234,847.4	29.7	305,451.7	38.6	485,503.1	61.4
	42.	Madagascar	0.0	0.0	27,759.2	4.7	82,859.8	13.9	30,586.3	5.1	141,205.3	23.8	453,335.9	76.2
	43.	Zimbabwe	0.0	0.0	0.0	0.0	114,266.3	29.1	150,630.4	38.4	264,896.7	67.5	127,823.1	32.5
	44.	Namibia	76,009.1	9.2	270,400.0	32.7	450,453.0	54.4	30,098.5	3.6	826,960.6	99.9	968.9	0.1
	45.	Botswana	0.0	0.0	26,174.5	4.5	484,647.3	83.4	70,027.9	12.1	580,849.6	100.0	22.2	0.0
	46.	South Africa	5992.1	0.5	242,164.0	19.8	413,093.7	33.7	164,293.4	13.4	825,543.2	67.4	398,848.8	32.6
	47.	Swaziland	0.0	0.0	0.0	0.0	2558.1	14.7	5948.4	34.3	8506.5	49.0	8852.9	51.0
	48.	Lesotho	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30,558.8	100.0

(*continued on next page*)

Table 5 (*continued*)

	No.[a]	Country	Drylands/humid area (km²/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]
Current drylands (D2)	1.	Tunisia	11,601.9	7.5	99,081.6	63.8	38,874.4	25.0	3388.5	2.2	152,946.4	98.5	2306.8	1.5
	2.	Algeria	1,746,552.2	75.4	354,754.9	15.3	171,371.9	7.4	24,465.9	1.1	2,297,144.9	99.2	19,515.9	0.8
	3.	Morocco	15,675.5	3.8	182,184.6	43.9	190,872.4	46.0	17,616.0	4.2	406,348.4	98.0	8378.1	2.0
	4.	Libya	1,332,771.7	82.1	274,321.2	16.9	15,128.7	0.9	0.0	0.0	1,622,222.3	100.0	218.6	0.0
	5.	Egypt	880,603.3	89.2	105,190.3	10.6	0.0	0.0	0.0	0.0	985,793.5	99.8	1930.6	0.2
	6.	W. Sahara	244,648.8	91.1	23,508.0	8.8	0.0	0.0	0.0	0.0	268,156.8	99.9	336.5	0.1
	7.	Mauritania	553,276.8	52.9	487,576.0	46.6	4930.6	0.5	0.0	0.0	1,045,783.4	99.9	665.7	0.1
	8.	Mali	392,532.2	31.2	495,989.9	39.5	274,338.8	21.8	91,307.4	7.3	1,254,168.3	99.8	2953.8	0.2
	9.	Niger	600,810.0	50.5	516,826.6	43.4	72,513.3	6.1	0.0	0.0	1,190,149.9	100.0	0.0	0.0
	10.	Chad	485,213.4	38.0	399,598.3	31.3	334,573.6	26.2	55,769.1	4.4	1,275,154.4	99.8	2120.5	0.2
	11.	Sudan	682,790.5	36.3	761,552.0	40.4	436,201.6	23.2	2076.6	0.1	1,882,620.7	100.0	262.5	0.0
	12.	Eritrea	129.9	0.1	76,250.6	63.3	43,331.7	35.9	79.7	0.1	119,791.8	99.4	742.6	0.6
	13.	Cape Verde	0.0	0.0	1648.1	40.1	2083.7	50.6	86.5	2.1	3818.3	92.8	296.1	7.2
	14.	Senegal	0.0	0.0	40,868.5	20.7	123,503.9	62.6	30,112.1	15.3	194,484.5	98.5	2928.4	1.5
	15.	Burkina Faso	0.0	0.0	14,672.8	5.3	215,227.8	77.8	46,582.5	16.8	276,483.1	100.0	0.0	0.0
	16.	Ethiopia	0.0	0.0	312,570.3	27.5	388,719.9	34.2	146,665.2	12.9	847,955.4	74.5	290,309.4	25.5
	17.	Nigeria	0.0	0.0	29,470.0	3.2	299,625.0	32.8	215,990.6	23.6	545,085.7	59.7	368,693.6	40.3
	18.	Gambia	0.0	0.0	0.0	0.0	9792.9	91.0	929.3	8.6	10,722.2	99.6	38.5	0.4
	19.	Cameroon	0.0	0.0	3968.6	0.8	38,958.3	8.3	23,304.1	5.0	66,231.0	14.1	402,870.0	85.9
	20.	Djibouti	0.0	0.0	21,242.1	97.4	542.4	2.5	0.0	0.0	21,784.5	99.8	35.5	0.2
	21.	Guinea-Bissau	0.0	0.0	0.0	0.0	0.0	0.0	2129.9	6.3	2129.9	6.3	31,889.1	93.7
	22.	Guinea	0.0	0.0	0.0	0.0	0.0	0.0	26,932.1	10.9	26,932.1	10.9	219,273.3	89.1
	23.	Benin	0.0	0.0	0.0	0.0	20,587.2	17.7	89,234.4	76.8	109,821.6	94.5	6334.7	5.5
	24.	South Sudan	0.0	0.0	160.1	0.0	413,072.4	65.0	141,369.0	22.2	554,601.5	87.2	81,288.8	12.8
	25.	Somalia	32,583.8	5.1	428,678.2	67.3	175,191.3	27.5	0.0	0.0	636,453.3	99.9	417.4	0.1
	26.	Ghana	0.0	0.0	0.0	0.0	4405.4	1.8	94,938.1	39.6	99,343.5	41.4	140,522.7	58.6
	27.	Togo	0.0	0.0	0.0	0.0	935.1	1.6	29,658.5	51.7	30,593.5	53.3	26,768.6	46.7
	28.	Central Afr. R.	0.0	0.0	0.0	0.0	47,036.9	7.5	139,217.3	22.3	186,254.1	29.8	437,958.7	70.2
	29.	Ivory Coast	0.0	0.0	0.0	0.0	0.0	0.0	107,070.9	33.1	107,070.9	33.1	216,647.9	66.9
	30.	D.R. of Congo	0.0	0.0	0.0	0.0	10,235.5	0.4	172,050.9	7.3	182,286.4	7.8	2,161,327.6	92.2
	31.	Kenya	0.0	0.0	223,375.5	38.1	254,716.7	43.5	48,170.1	8.2	526,262.4	89.9	59,396.2	10.1
	32.	Uganda	0.0	0.0	0.0	0.0	22,597.1	9.3	71,943.1	29.6	94,540.2	38.9	148,509.2	61.1
	33.	R. of Congo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	343,954.0	100.0
	34.	STP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1009.0	100.0
	35.	Tanzania	0.0	0.0	0.0	0.0	258,884.9	27.3	373,924.0	39.4	632,808.9	66.8	315,121.9	33.2
	36.	Rwanda	0.0	0.0	0.0	0.0	0.0	0.0	10,494.0	41.3	10,494.0	41.3	14,935.5	58.7
	37.	Burundi	0.0	0.0	0.0	0.0	0.0	0.0	4761.2	17.5	4761.2	17.5	22,381.0	82.5
	38.	Angola	1703.0	0.1	38,098.0	3.0	379,575.8	30.2	243,272.1	19.4	662,648.9	52.8	592,633.8	47.2
	39.	Zambia	0.0	0.0	0.0	0.0	217,982.5	28.8	275,957.2	36.5	493,939.6	65.4	261,868.9	34.6
	40.	Malawi	0.0	0.0	0.0	0.0	7053.7	5.9	54,264.8	45.7	61,318.5	51.7	57,399.5	48.3
	41.	Mozambique	0.0	0.0	218.3	0.0	243,948.5	30.8	287,571.8	36.4	531,738.5	67.2	259,216.3	32.8
	42.	Madagascar	0.0	0.0	38.7	0.0	125,388.7	21.1	43,001.2	7.2	168,428.6	28.3	426,112.6	71.7
	43.	Zimbabwe	0.0	0.0	3747.4	1.0	321,108.4	81.8	58,172.8	14.8	383,028.7	97.5	9691.1	2.5
	44.	Namibia	46,575.0	5.6	457,495.6	55.3	323,390.8	39.1	0.0	0.0	827,461.4	99.9	468.1	0.1
	45.	Botswana	0.0	0.0	162,274.1	27.9	418,597.7	72.1	0.0	0.0	580,871.8	100.0	0.0	0.0
	46.	South Africa	181.4	0.0	381,420.9	31.2	610,214.2	49.8	140,170.0	11.4	1,131,986.5	92.5	92,405.5	7.5
	47.	Swaziland	0.0	0.0	0.0	0.0	7124.9	41.0	4239.9	24.4	11,364.8	65.5	5994.6	34.5
	48.	Lesotho	0.0	0.0	0.0	0.0	4068.7	13.3	15,579.1	51.0	19,647.8	64.3	10,911.0	35.7

(*continued on next page*)

Table 5 (*continued*)

	No.[a]	Country	Drylands/humid area (km²/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]
Differences D2-D1	1.	Tunisia	+6678.3	+4.3	−3093.2	−2.0	+4168.3	+2.7	−8135.4	−5.2	−382.0	−0.2	+382.0	+0.2
	2.	Algeria	−31,558.1	−1.4	+59,006.2	+2.5	+58,997.6	+2.5	−45,621.1	−2.0	+40,824.6	+1.8	−40,824.6	−1.8
	3.	Morocco	+15,675.5	+3.8	+59,142.8	+14.3	−801.8	−0.2	−51,124.7	−12.3	+22,891.7	+5.5	−22,891.7	−5.5
	4.	Libya	+79,242.5	+4.9	−60,067.5	−3.7	−19,076.5	−1.2	0.0	0.0	+99.1	+0.0	−99.1	−0.0
	5.	Egypt	−34,866.9	−3.5	+35,745.3	+3.6	−158.6	0.0	0.0	0.0	+719.7	+0.1	−719.7	−0.1
	6.	W. Sahara	+17,980.9	+6.7	−17,749.1	−6.6	0.0	0.0	0.0	0.0	+231.8	+0.1	−231.8	−0.1
	7.	Mauritania	−16,193.4	−1.5	+32,552.6	+3.1	−16,149.6	−1.5	0.0	0.0	+209.6	+0.0	−209.6	−0.0
	8.	Mali	+153,862.5	+12.2	−149,188.6	−11.9	+13,283.0	+1.1	−9708.2	−0.8	+8248.7	+0.7	−8248.7	−0.7
	9.	Niger	+150,483.9	+12.6	+18,608.2	+1.6	−169,038.2	−14.2	0.0	0.0	+53.8	+0.0	−53.8	−0.0
	10.	Chad	+88,691.9	+6.9	+34,464.7	+2.7	−23,268.6	−1.8	−92,806.3	−7.3	+7081.7	+0.6	−7081.7	−0.6
	11.	Sudan	−26,630.5	−1.4	+144,557.0	+7.7	−83,645.0	−4.4	−34,147.5	−1.8	+134.0	+0.0	−134.0	−0.0
	12.	Eritrea	−18,745.5	−15.6	−12,931.6	−10.7	+32,612.8	+27.1	+79.7	+0.1	+1015.2	+0.8	−1015.2	−0.8
	13.	Cape Verde	−375.1	−9.1	−274.5	−6.7	+2083.7	+50.6	+86.5	+2.1	+1520.5	+37.0	−1520.5	−37.0
	14.	Senegal	0.0	0.0	−11,993.4	−6.1	+33,363.6	+16.9	−13,839.8	−7.0	+7530.5	+3.8	−7530.5	−3.8
	15.	Burkina Faso	0.0	0.0	+7252.3	+2.6	−2810.1	−1.0	−4454.1	−1.6	−11.8	−0.0	+11.8	+0.0
	16.	Ethiopia	−9450.3	−0.8	+104,327.2	+9.2	+109,726.0	+9.6	−23,531.8	−2.1	+181,071.1	+15.9	−181,071.1	−15.9
	17.	Nigeria	0.0	0.0	+11,193.9	+1.2	+50,696.8	+5.5	−49,367.6	−5.4	+12,523.2	+1.4	−12,523.2	−1.4
	18.	Gambia	0.0	0.0	0.0	0.0	+8332.9	+77.4	−8160.1	−75.8	+172.8	+1.6	−172.8	−1.6
	19.	Cameroon	0.0	0.0	+1097.8	+0.2	+5608.3	+1.2	−1870.8	−0.4	+4835.3	+1.0	−4835.3	−1.0
	20.	Djibouti	−4905.0	−22.5	+5408.1	+24.8	−462.7	−2.1	0.0	0.0	+40.4	+0.2	−40.4	−0.2
	21.	Guinea-Bissau	0.0	0.0	0.0	0.0	0.0	0.0	+100.1	+0.3	+100.1	+0.3	−100.1	−0.3
	22.	Guinea	0.0	0.0	0.0	0.0	0.0	0.0	−7461.2	−3.0	−7461.2	−3.0	+7461.2	+3.0
	23.	Benin	0.0	0.0	0.0	0.0	+3871.8	+3.3	+2765.6	+2.4	+6637.3	+5.7	−6637.3	−5.7
	24.	South Sudan	0.0	0.0	−1590.8	−0.3	+105,835.9	+16.6	−57,372.4	−9.0	+46,872.6	+7.4	−46,872.6	−7.4
	25.	Somalia	−77,938.9	−12.2	+27,177.3	+4.3	+51,058.0	+8.0	0.0	0.0	+296.4	+0.0	−296.4	−0.0
	26.	Ghana	0.0	0.0	0.0	0.0	−50,484.1	−21.0	−11,229.7	−4.7	−61,713.8	−25.7	+61,713.8	+25.7
	27.	Togo	0.0	0.0	0.0	0.0	−4778.2	−8.3	+16,018.4	+27.9	+11,240.2	+19.6	−11,240.2	−19.6
	28.	Central Afr. R.	0.0	0.0	0.0	0.0	+24,761.3	+4.0	+35,577.0	+5.7	+60,338.2	+9.7	−60,338.2	−9.7
	29.	Ivory Coast	0.0	0.0	0.0	0.0	0.0	0.0	−15,910.8	−4.9	−15,910.8	−4.9	+15,910.8	+4.9
	30.	D.R. of Congo	0.0	0.0	0.0	0.0	+10,235.5	+0.4	+160,319.2	+6.8	+170,554.7	+7.3	−170,554.7	−7.3
	31.	Kenya	0.0	0.0	+92,955.9	+15.9	+47,098.1	+8.0	−32,140.4	−5.5	+107,913.7	+18.4	−107,913.7	−18.4
	32.	Uganda	0.0	0.0	0.0	0.0	+21,239.9	+8.7	+66,654.2	+27.4	+87,894.1	+36.2	−87,894.1	−36.2
	33.	R. of Congo	0.0	0.0	0.0	0.0	0.0	0.0	−1231.5	−0.4	−1231.5	−0.4	+1231.5	+0.4
	34.	STP	0.0	0.0	0.0	0.0	−811.5	−80.4	0.0	0.0	−811.5	−80.4	+811.5	+80.4
	35.	Tanzania	0.0	0.0	0.0	0.0	+258,884.9	+27.3	+277,111.4	+29.2	+535,996.3	+56.5	−535,996.3	−56.5
	36.	Rwanda	0.0	0.0	0.0	0.0	0.0	0.0	+10,494.0	+41.3	+10,494.0	+41.3	−10,494.0	−41.3
	37.	Burundi	0.0	0.0	0.0	0.0	0.0	0.0	+4761.2	+17.5	+4761.2	+17.5	−4761.2	−17.5
	38.	Angola	+1703.0	+0.1	+38,098.0	+3.0	+282,067.6	+22.5	+97,169.5	+7.7	+419,038.0	+33.4	−419,038.0	−33.4
	39.	Zambia	0.0	0.0	0.0	0.0	+212,609.4	+28.1	+157,705.6	+20.9	+370,314.9	+49.0	−370,314.9	−49.0
	40.	Malawi	0.0	0.0	0.0	0.0	+7053.7	+5.9	+54,264.8	+45.7	+61,318.5	+51.7	−61,318.5	−51.7
	41.	Mozambique	0.0	0.0	+218.3	+0.0	+173,344.2	+21.9	+52,724.4	+6.7	+226,286.8	+28.6	−226,286.8	−28.6
	42.	Madagascar	0.0	0.0	−27,720.5	−4.7	+42,528.9	+7.2	+12,414.9	+2.1	+27,223.3	+4.6	−27,223.3	−4.6
	43.	Zimbabwe	0.0	0.0	+3747.4	+1.0	+206,842.1	+52.7	−92,457.6	−23.5	+118,132.0	+30.1	−118,132.0	−30.1
	44.	Namibia	−29,434.1	−3.6	+187,095.6	+22.6	−127,062.2	−15.3	−30,098.5	−3.6	+500.8	+0.1	−500.8	−0.1

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Table 5 (*continued*)

No.[a]	Country	Drylands/humid area (km²/% of the country area)											
		Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
		(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]	(km²)[b]	(%)[c]
45.	Botswana	0.0	0.0	+136,099.6	+23.4	−66,049.6	−11.4	−70,027.9	−12.1	+22.2	+0.0	−22.2	−0.0
46.	South Africa	−5810.7	−0.5	+139,256.9	+11.4	+197,120.5	+16.1	−24,123.4	−2.0	+306,443.3	+25.0	−306,443.3	−25.0
47.	Swaziland	0.0	0.0	0.0	0.0	+4566.8	+26.3	−1708.5	−9.8	+2858.3	+16.5	−2858.3	−16.5
48.	Lesotho	0.0	0.0	0.0	0.0	+4068.7	+13.3	+15,579.1	+51.0	+19,647.8	+64.3	−19,647.8	−64.3

Note: Country abbreviations: W. Sahara – Western Sahara, Central Afr. R. – Central African Republic, D.R. of Congo – Democratic Republic of the Congo; R. of Congo – Republic of the Congo; STP – São Tomé and Príncipe; Differences D2-D1 – differences between D2 and D1 (positive/negative values indicate larger/smaller surfaces of drylands in the current database compared with the initial database); in the case of percentage-based differences, certain possible minor inconsistencies of results obtained from differences D2-D1 are due to values with a single decimal point (the differences were obtained based on more detailed percentage values, with four decimal points, which were not included in this table).

[a] The states are listed in a descending order considering the maximum latitude values of northern limits.

[b] Absolute values of drylands area.

[c] Percentage of absolute drylands area in relation to the state area.

these factors, since this paper's aim was to analyze the hypothesis that the planet is in fact more arid that previously assessed, regardless of the causes that generated this climatic outcome.

However, even under these conditions, we believe that post-1980 climate warming is the most important cause of dryland expansion, especially given that other studies that approached global aridity changes (trends) supported this hypothesis. Therefore, a series of studies have confirmed, either directly or indirectly, that dryland expansion is already real and is a result of global warming (Feng and Fu, 2013; Ji et al., 2015; Prăvălie, 2016; Huang et al., 2017a, 2017b). Moreover, the findings of other studies are also consistent with the global spatial change pattern of dryland systems, identified in this study. For instance, a recent study (Zarch et al., 2015) that analyzed changes in global aridity, including the post-1980 period, highlighted obvious drier trends in Alaska, Northern Canada and, in part, in Northeastern Russia, which is generally consistent with our results (which also highlighted these epicentres of drier trends in these northern hemisphere regions). Similarly to our assumptions, it was interpreted that these mentioned changes (as well as others recorded globally) can be attributed to an overall post-1980 climate warming, which most likely was the key factor in the increase of PET values and implicitly of aridity (Zarch et al., 2015). Also, another representative study generally supports our findings, for instance regarding the spatial pattern of transitions between arid and humid environments. One of the findings of a relatively recent study was that, in the past decades, extensive areas in Eastern Asia became drier (especially in China), while vast sectors of Northern and Northwestern Asia, and Eastern and Northeastern Europe, became wetter (Greve et al., 2014), which is consistent with our study's results.

Therefore, it seems that the scenario of a more arid world is real and currently affecting, to varying degrees of severity, 126 states worldwide (Prăvălie, 2016). What is highly interesting and alarming about the stability of the Earth's climate system is the fact that large areas with new aridity expansion are located mainly at high northern latitudes, above the 60°N parallel, previously known as the northern limit of aridity (Safriel et al., 2005). The northern migration of arid environments is a major threat to planetary health as a result of positive warming feedbacks that can be triggered by the interaction between drylands and other systems located in this vast region of the planet. The feedbacks relate to snow cover, permafrost, peatlands and boreal forests.

The drier conditions already decrease land surface albedo in the Arctic due to the rapid decline of snow cover period (Bokhorst et al., 2016), which can determine by up to 90% higher absorption of incident solar radiation by darker surfaces (IPCC, 2007). Permafrost thawing is another serious cryosphere-related risk generated by a warmer and more arid climate in high-latitude regions. The massive carbon stocks in frozen soils that are estimated to total ~1700 Gt (gigatons or billion tons) (Schuur et al., 2015), which is more than twice the carbon our atmosphere contains today (over 700 Gt) (Zimov et al., 2006). It appears that the Yedoma permafrost, largely overlapping drylands in northeastern Siberia and Central Alaska, is already starting to release carbon from its massive (~500 Gt), extensive (> 1 mil km²) and extremely high carbon content (which can be even 30 times higher than that of non-permafrost soils) deposits (Zimov et al., 2006; Strauss et al., 2017).

However, these implications do not tell us the whole story of high-latitude aridity consequences. Large carbon pools in northern peatlands (northern Eurasia and North America), estimated to total ~550 Gt (Yu et al., 2010), are particularly vulnerable to drier conditions, mainly through fires, as was already noticed during tropical peatland fires (which total an additional ~50 Gt C) in 1997, when forest and underlying peat fires in Indonesia alone released up to 2.6 Gt C (Page et al., 2002). Coupled with the effects generated by large-scale insect infestations, e.g. in western Canada, where tens of millions of hectares of vegetation were devastated (Boyd et al., 2013) and hundreds of millions of tons of carbon were released into the atmosphere (Kurz et al., 2008),

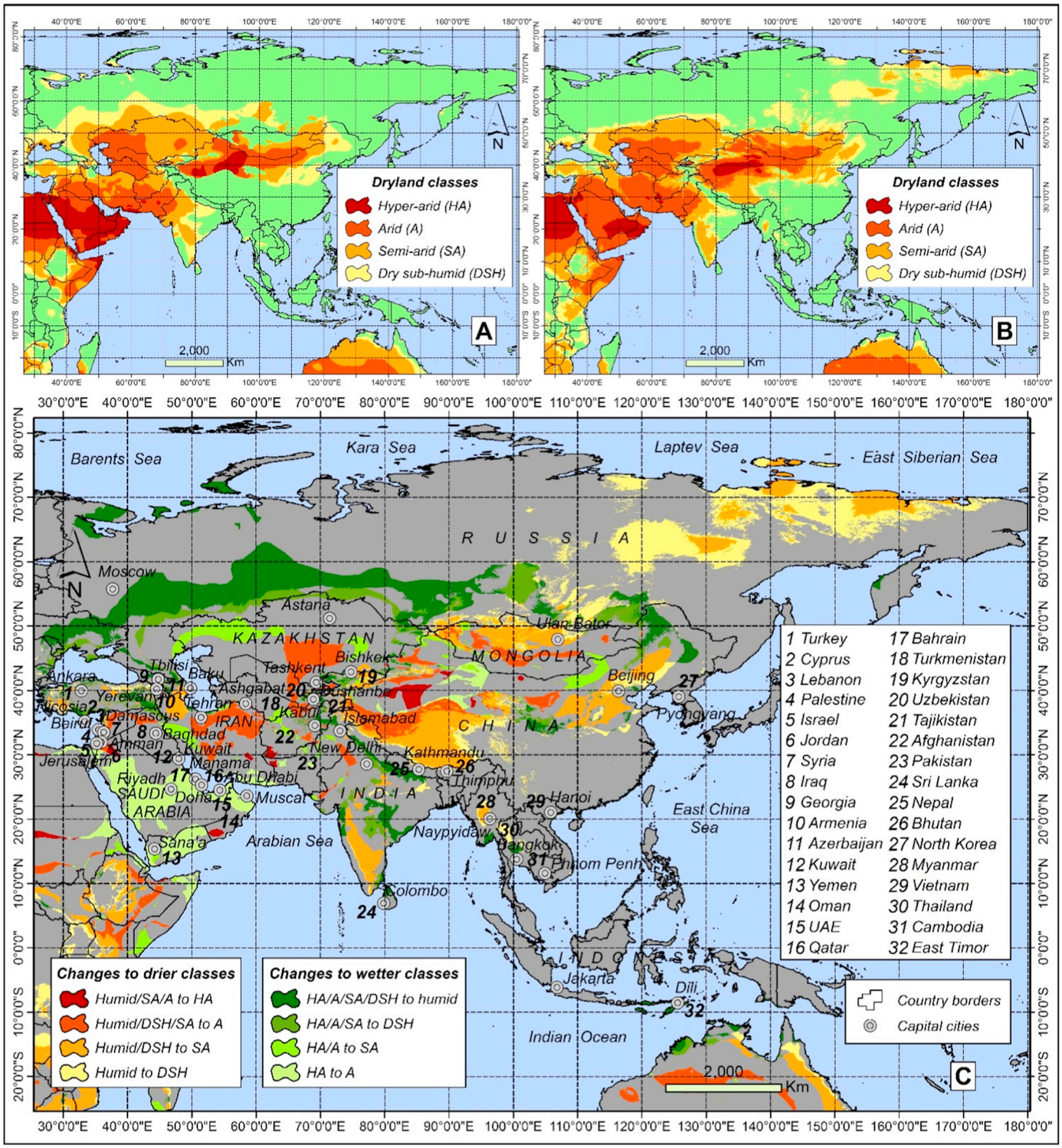

Fig. 6. Previous estimates (a) of the Asian drylands (spatial data processed after Middleton and Thomas, 1997) versus current estimates (b), based on a new global AI database (data processed after Trabucco and Zomer, 2009) and spatial differences between these two databases (c). Note: in maps a and b, light green reveals humid areas, while in map c gray shows areas without changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fires are also a tremendous threat for boreal forests, in a drier world.

A significant increase of these feedbacks is expected by the end of the century, when advanced simulations (under business-as-usual RCP8.5 scenario) show a dryland expansion up to 56% of the global terrestrial area (8.3%, 20.3%, 14.9% and 12.6% for DSH, SA, A and HA areas, respectively), which is dominant by far at high-latitudes (Huang et al., 2016). Even in a relatively optimistic scenario (RCP4.5), ~50% of the global terrestrial area will be under the pressure of aridity conditions (8.9%, 19%, 14.4% and 8.4% for the four systems) (Huang et al., 2016). At the same time, the expansion of arid and hyper-arid systems at lower latitudes will most likely set off a humanitarian crisis associated to the increase of food insecurity, poverty, human migration and

Table 6
Drylands and humid areas extent in absolute and relative values at state level in Asia – initial drylands area/current drylands area/difference between the initial and current dryland areas.

	No.[a]	Country	Drylands/humid area (km^2/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]	(km^2)[d]	(%)[e]
Initial drylands (D1)	1.	Russia[b]	0.0	0.0	0.0	0.0	1,004,873.3	7.8	1,069,157.4	8.3	2,074,030.7	16.0	10,872,308.1	84.0
	2.	Kazakhstan	0.0	0.0	883,224.9	32.4	1,791,799.6	65.7	20,969.8	0.8	2,695,994.2	98.8	32,506.9	1.2
	3.	China	503,495.3	5.4	1,240,238.0	13.2	876,007.8	9.3	1,071,787.6	11.4	3,691,528.8	39.3	5,708,590.8	60.7
	4.	Mongolia	1670.0	0.1	490,204.1	31.3	527,727.5	33.7	0.0	0.0	1,019,601.6	65.1	546,028.1	34.9
	5.	Uzbekistan	0.0	0.0	284,859.2	63.7	149,194.4	33.3	10,048.5	2.2	444,102.1	99.3	3340.3	0.7
	6.	Georgia	0.0	0.0	0.0	0.0	3447.2	4.9	20,183.4	28.9	23,630.6	33.8	46,259.9	66.2
	7.	Kyrgyzstan	0.0	0.0	4878.8	2.4	78,240.2	39.2	25,902.2	13.0	109,021.1	54.6	90,673.0	45.4
	8.	North Korea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	122,896.4	100.0
	9.	Turkmenistan	0.0	0.0	452,001.6	92.2	17,532.4	3.6	0.0	0.0	469,534.0	95.8	20,729.8	4.2
	10.	Turkey	0.0	0.0	0.0	0.0	358,982.9	45.9	256,373.8	32.8	615,356.7	78.7	166,470.7	21.3
	11.	Azerbaijan	0.0	0.0	0.0	0.0	29,234.5	33.8	39,833.2	46.1	69,067.7	80.0	17,303.0	20.0
	12.	Armenia	0.0	0.0	0.0	0.0	5745.0	19.4	23,371.4	78.7	29,116.4	98.1	567.5	1.9
	13.	Tajikistan	0.0	0.0	0.0	0.0	33,822.4	23.8	23,251.1	16.4	57,073.6	40.1	85,129.6	59.9
	14.	Iran	74,930.8	4.6	874,715.1	53.8	574,847.7	35.3	20,525.7	1.3	1,545,019.3	95.0	81,336.8	5.0
	15.	Afghanistan	0.0	0.0	308,271.1	47.8	293,305.5	45.4	5318.5	0.8	606,895.1	94.0	38,619.5	6.0
	16.	Iraq	0.0	0.0	353,653.5	79.2	92,778.2	20.8	0.0	0.0	446,431.6	100.0	138.0	0.0
	17.	Syria	0.0	0.0	92,906.1	49.7	76,721.1	41.0	13,948.5	7.5	183,575.7	98.2	3339.8	1.8
	18.	Pakistan	36,694.4	4.2	598,944.2	68.3	113,233.9	12.9	15,624.0	1.8	764,496.4	87.2	112,636.1	12.8
	19.	Cyprus	0.0	0.0	825.7	8.9	8246.2	88.8	0.0	0.0	9071.9	97.7	217.5	2.3
	20.	India	0.0	0.0	160,518.1	5.1	941,532.1	29.7	775,031.6	24.5	1,877,081.8	59.3	1,289,917.8	40.7
	21.	Lebanon	0.0	0.0	0.0	0.0	2716.6	26.0	4338.5	41.5	7055.2	67.5	3391.1	32.5
	22.	Israel	5752.6	25.6	552.3	2.5	16,030.8	71.3	0.0	0.0	22,335.7	99.4	135.5	0.6
	23.	Jordan	24,809.6	27.8	31,684.3	35.4	32,887.3	36.8	0.0	0.0	89,381.3	100.0	13.0	0.0
	24.	Palestine[c]	0.0	0.0	0.0	0.0	6245.9	100.1	0.0	0.0	6245.9	100.1	−7.4	−0.1
	25.	Saudi Arabia	1,460,053.1	76.2	454,023.8	23.7	105.0	0.0	0.0	0.0	1,914,181.9	99.8	2955.1	0.2
	26.	Nepal	0.0	0.0	0.0	0.0	0.0	0.0	13,666.3	9.2	13,666.3	9.2	134,545.6	90.8
	27.	Kuwait	86.4	0.5	16,343.6	93.7	0.0	0.0	0.0	0.0	16,430.0	94.2	1019.9	5.8
	28.	Myanmar	0.0	0.0	0.0	0.0	0.0	0.0	22,929.6	3.4	22,929.6	3.4	649,644.1	96.6
	29.	Bhutan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40,149.6	100.0
	30.	Oman	261,469.2	84.1	47,557.6	15.3	0.0	0.0	0.0	0.0	309,026.8	99.4	1764.7	0.6
	31.	Bahrain	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	668.2	100.0
	32.	Qatar	10,850.2	96.2	0.0	0.0	0.0	0.0	0.0	0.0	10,850.2	96.2	425.4	3.8
	33.	U.A.E.	78,251.1	98.3	0.0	0.0	0.0	0.0	0.0	0.0	78,251.1	98.3	1356.4	1.7
	34.	Vietnam	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	330,215.4	100.0
	35.	Thailand	0.0	0.0	0.0	0.0	0.0	0.0	34,835.1	6.7	34,835.1	6.7	482,195.2	93.3
	36.	Yemen	319,936.0	70.3	133,140.6	29.3	0.0	0.0	0.0	0.0	453,076.7	99.6	1714.9	0.4
	37.	Cambodia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	182,457.3	100.0
	38.	Sri Lanka	0.0	0.0	0.0	0.0	2672.9	4.0	18,724.5	28.3	21,397.4	32.3	44,867.9	67.7
	39.	Indonesia	0.0	0.0	0.0	0.0	0.0	0.0	52,376.3	2.8	52,376.3	2.8	1,849,906.2	97.2
	40.	East Timor	0.0	0.0	0.0	0.0	0.0	0.0	14,556.6	97.0	14,556.6	97.0	451.7	3.0

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Table 6 (*continued*)

	No.[a]	Country	Drylands/humid area (km²/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km²)[d]	(%)[e]	(km²)[d]	(%)[e]	(km²)[d]	(%)[e]	(km²)[d]	(%)[e]	(km²)[d]	(%)[e]	(km²)[d]	(%)[e]
Current drylands (D2)	1.	Russia[b]	0.0	0.0	16.6	0.0	549,580.0	4.2	2,389,145.8	18.5	2,938,742.4	22.7	10,007,596.4	77.3
	2.	Kazakhstan	0.0	0.0	893,957.2	32.8	1,673,351.8	61.3	102,317.4	3.7	2,669,626.4	97.8	58,874.7	2.2
	3.	China	477,075.6	5.1	1,594,841.7	17.0	2,150,070.6	22.9	1,086,802.9	11.6	5,308,790.9	56.5	4,091,328.7	43.5
	4.	Mongolia	60.2	0.0	637,165.9	40.7	790,856.1	50.5	94,963.1	6.1	1,523,045.3	97.3	42,584.4	2.7
	5.	Uzbekistan	0.0	0.0	357,211.6	79.8	72,717.8	16.3	5350.0	1.2	435,279.4	97.3	12,163.0	2.7
	6.	Georgia	0.0	0.0	0.0	0.0	2903.5	4.2	6719.8	9.6	9623.4	13.8	60,267.1	86.2
	7.	Kyrgyzstan	0.0	0.0	815.6	0.4	91,012.4	45.6	48,710.2	24.4	140,538.2	70.4	59,155.9	29.6
	8.	North Korea	0.0	0.0	0.0	0.0	0.0	0.0	48.1	0.0	48.1	0.0	122,848.3	100.0
	9.	Turkmenistan	0.0	0.0	457,523.6	93.3	32,679.0	6.7	51.9	0.0	490,254.6	100.0	9.2	0.0
	10.	Turkey	0.0	0.0	0.0	0.0	302,909.5	38.7	254,306.1	32.5	557,215.6	71.3	224,611.8	28.7
	11.	Azerbaijan	0.0	0.0	0.0	0.0	54,882.5	63.5	16,918.6	19.6	71,801.1	83.1	14,569.6	16.9
	12.	Armenia	0.0	0.0	0.0	0.0	8008.7	27.0	10,413.3	35.1	18,422.0	62.1	11,261.9	37.9
	13.	Tajikistan	0.0	0.0	11,998.6	8.4	41,921.9	29.5	14,792.0	10.4	68,712.4	48.3	73,490.8	51.7
	14.	Iran	12,049.5	0.7	1,211,665.2	74.5	374,077.5	23.0	15,048.5	0.9	1,612,840.6	99.2	13,515.5	0.8
	15.	Afghanistan	23,194.8	3.6	293,898.3	45.5	232,347.1	36.0	24,169.3	3.7	573,609.5	88.9	71,905.1	11.1
	16.	Iraq	0.0	0.0	381,766.4	85.5	39,649.7	8.9	20,100.6	4.5	441,516.7	98.9	5052.9	1.1
	17.	Syria	0.0	0.0	137,652.2	73.6	40,309.8	21.6	2545.3	1.4	180,507.2	96.6	6408.3	3.4
	18.	Pakistan	13,257.1	1.5	629,920.8	71.8	151,901.2	17.3	27,436.8	3.1	822,515.8	93.8	54,616.7	6.2
	19.	Cyprus	0.0	0.0	0.0	0.0	7021.5	75.6	1258.9	13.6	8280.5	89.1	1008.9	10.9
	20.	India	0.0	0.0	220,459.6	7.0	1,010,213.5	31.9	587,358.0	18.5	1,818,031.0	57.4	1,348,968.6	42.6
	21.	Lebanon	0.0	0.0	0.0	0.0	1926.2	18.4	1687.7	16.2	3613.9	34.6	6832.4	65.4
	22.	Israel	733.0	3.3	11,965.6	53.2	8361.7	37.2	946.1	4.2	22,006.5	97.9	464.7	2.1
	23.	Jordan	23,553.4	26.3	59,770.3	66.9	6066.1	6.8	0.0	0.0	89,389.9	100.0	4.4	0.0
	24.	Palestine[c]	0.0	0.0	1762.0	28.2	4465.9	71.6	0.0	0.0	6227.9	99.8	10.6	0.2
	25.	Saudi Arabia	563,404.2	29.4	1,352,216.0	70.5	271.9	0.0	0.0	0.0	1,915,892.1	99.9	1244.9	0.1
	26.	Nepal	0.0	0.0	0.0	0.0	2033.0	1.4	6959.5	4.7	8992.5	6.1	139,219.4	93.9
	27.	Kuwait	0.0	0.0	17,283.2	99.0	0.0	0.0	0.0	0.0	17,283.2	99.0	166.7	1.0
	28.	Myanmar	0.0	0.0	0.0	0.0	36,645.9	5.4	38,009.5	5.7	74,655.4	11.1	597,918.3	88.9
	29.	Bhutan	0.0	0.0	0.0	0.0	6335.6	15.8	4061.9	10.1	10,397.4	25.9	29,752.2	74.1
	30.	Oman	180,077.6	57.9	129,232.3	41.6	1115.9	0.4	0.0	0.0	310,425.9	99.9	365.6	0.1
	31.	Bahrain	0.0	0.0	567.2	84.9	0.0	0.0	0.0	0.0	567.2	84.9	101.0	15.1
	32.	Qatar	0.0	0.0	10,977.7	97.4	0.0	0.0	0.0	0.0	10,977.7	97.4	297.9	2.6
	33.	U.A.E.	8872.1	11.1	69,724.2	87.6	0.0	0.0	0.0	0.0	78,596.4	98.7	1011.1	1.3
	34.	Vietnam	0.0	0.0	0.0	0.0	0.0	0.0	1522.6	0.5	1522.6	0.5	328,692.8	99.5
	35.	Thailand	0.0	0.0	0.0	0.0	315.3	0.1	63,874.5	12.4	64,189.8	12.4	452,840.5	87.6
	36.	Yemen	22,198.3	4.9	415,175.4	91.3	16,957.8	3.7	0.0	0.0	454,331.5	99.9	460.1	0.1
	37.	Cambodia	0.0	0.0	0.0	0.0	0.0	0.0	621.7	0.3	621.7	0.3	181,835.6	99.7
	38.	Sri Lanka	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66,265.3	100.0
	39.	Indonesia	0.0	0.0	0.0	0.0	486.2	0.0	3394.4	0.2	3880.6	0.2	1,898,401.9	99.8
	40.	East Timor	0.0	0.0	0.0	0.0	52.1	0.3	338.5	2.3	390.6	2.6	14,617.7	97.4

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Table 6 (*continued*)

	No.[a]	Country	Drylands/humid area (km²/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km²)[d]	(%)[e]	(km²)[d]	(%)[e]	(km²)[d]	(%)[e]	(km²)[d]	(%)[e]	(km²)[d]	(%)[e]	(km²)[d]	(%)[e]
Differences D2-D1	1.	Russia[b]	0.0	0.0	+16.6	+0.0	−455,293.3	−3.5	+1,319,988.4	+10.2	+864,711.7	+6.7	−864,711.7	−6.7
	2.	Kazakhstan	0.0	0.0	+10,732.3	+0.4	−118,447.8	−4.3	+81,347.6	+3.0	−26,367.8	−1.0	+26,367.8	+1.0
	3.	China	−26,419.7	−0.3	+354,603.7	+3.8	+1,274,062.8	+13.6	+15,015.3	+0.2	+1,617,262.1	+17.2	−1,617,262.1	−17.2
	4.	Mongolia	−1609.8	−0.1	+146,961.8	+9.4	+263,128.6	+16.8	+94,963.1	+6.1	+503,443.7	+32.2	−503,443.7	−32.2
	5.	Uzbekistan	0.0	0.0	+72,352.4	+16.2	−76,476.6	−17.1	−4698.5	−1.1	−8822.7	−2.0	+8822.7	+2.0
	6.	Georgia	0.0	0.0	0.0	0.0	−543.7	−0.8	−13,463.6	−19.3	−14,007.2	−20.0	+14,007.2	+20.0
	7.	Kyrgyzstan	0.0	0.0	−4063.2	−2.0	+12,772.2	+6.4	+22,808.0	+11.4	+31,517.1	+15.8	−31,517.1	−15.8
	8.	North Korea	0.0	0.0	0.0	0.0	0.0	0.0	+48.1	+0.0	+48.1	+0.0	−48.1	−0.0
	9.	Turkmenistan	0.0	0.0	+5522.0	+1.1	+15,146.6	+3.1	+51.9	+0.0	+20,720.6	+4.2	−20,720.6	−4.2
	10.	Turkey	0.0	0.0	0.0	0.0	−56,073.4	−7.2	−2067.7	−0.3	−58,141.1	−7.4	+58,141.1	+7.4
	11.	Azerbaijan	0.0	0.0	0.0	0.0	+25,648.0	+29.7	−22,914.6	−26.5	+2733.4	+3.2	−2733.4	−3.2
	12.	Armenia	0.0	0.0	0.0	0.0	+2263.7	+7.6	−12,958.1	−43.7	−10,694.4	−36.0	+10,694.4	+36.0
	13.	Tajikistan	0.0	0.0	+11,998.6	+8.4	+8099.5	+5.7	−8459.1	−5.9	+11,638.8	+8.2	−11,638.8	−8.2
	14.	Iran	−62,881.3	−3.9	+336,950.1	+20.7	−200,770.2	−12.3	−5477.2	−0.3	+67,821.3	+4.2	−67,821.3	−4.2
	15.	Afghanistan	+23,194.8	+3.6	−14,372.8	−2.2	−60,958.4	−9.4	+18,850.8	+2.9	−33,285.6	−5.2	+33,285.6	+5.2
	16.	Iraq	0.0	0.0	+28,112.9	+6.3	−53,128.5	−11.9	+20,100.6	+4.5	−4914.9	−1.1	+4914.9	+1.1
	17.	Syria	0.0	0.0	+44,746.1	+23.9	−36,411.3	−19.5	−11,403.2	−6.1	−3068.5	−1.6	+3068.5	+1.6
	18.	Pakistan	−23,437.3	−2.7	+30,976.6	+3.5	+38,667.3	+4.4	+11,812.8	+1.3	+58,019.4	+6.6	−58,019.4	−6.6
	19.	Cyprus	0.0	0.0	−825.7	−8.9	−1224.7	−13.2	+1258.9	+13.6	−791.4	−8.5	+791.4	+8.5
	20.	India	0.0	0.0	+59,941.5	+1.9	+68,681.4	+2.2	−187,673.6	−5.9	−59,050.8	−1.9	+59,050.8	+1.9
	21.	Lebanon	0.0	0.0	0.0	0.0	−790.4	−7.6	−2650.8	−25.4	−3441.3	−32.9	+3441.3	+32.9
	22.	Israel	−5019.6	−22.3	+11,413.3	+50.8	−7669.1	−34.1	+946.1	+4.2	−329.2	−1.5	+329.2	+1.5
	23.	Jordan	−1256.2	−1.4	+28,086.0	+31.4	−26,821.2	−30.0	0.0	0.0	+8.6	+0.0	−8.6	−0.0
	24.	Palestine[c]	0.0	0.0	+1762.0	+28.2	−1780.0	−28.5	0.0	0.0	−18.0	−0.3	+18.0	+0.3
	25.	Saudi Arabia	−896,648.9	−46.8	+898,192.2	+46.9	+166.9	+0.0	0.0	0.0	+1710.2	+0.1	−1710.2	−0.1
	26.	Nepal	0.0	0.0	0.0	0.0	+2033.0	+1.4	−6706.8	−4.5	−4673.8	−3.2	+4673.8	+3.2
	27.	Kuwait	−86.4	−0.5	+939.6	+5.4	0.0	0.0	0.0	0.0	+853.2	+4.9	−853.2	−4.9
	28.	Myanmar	0.0	0.0	0.0	0.0	+36,645.9	+5.4	+15,079.9	+2.2	+51,725.8	+7.7	−51,725.8	−7.7
	29.	Bhutan	0.0	0.0	0.0	0.0	+6335.6	+15.8	+4061.9	+10.1	+10,397.4	+25.9	−10,397.4	−25.9
	30.	Oman	−81,391.6	−26.2	+81,674.7	+26.3	+1115.9	+0.4	0.0	0.0	+1399.1	+0.5	−1399.1	−0.5
	31.	Bahrain	0.0	0.0	+567.2	+84.9	0.0	0.0	0.0	0.0	+567.2	+84.9	−567.2	−84.9
	32.	Qatar	−10,850.2	−96.2	+10,977.7	+97.4	0.0	0.0	0.0	0.0	+127.5	+1.1	−127.5	−1.1
	33.	U.A.E.	−69,379.0	−87.2	+69,724.2	+87.6	0.0	0.0	0.0	0.0	+345.3	+0.4	−345.3	−0.4
	34.	Vietnam	0.0	0.0	0.0	0.0	0.0	0.0	+1522.6	+0.5	+1522.6	+0.5	−1522.6	−0.5
	35.	Thailand	0.0	0.0	0.0	0.0	+315.3	+0.1	+29,039.4	+5.6	+29,354.7	+5.7	−29,354.7	−5.7
	36.	Yemen	−297,737.7	−65.5	+282,034.8	+62.0	+16,957.8	+3.7	0.0	0.0	+1254.8	+0.3	−1254.8	−0.3
	37.	Cambodia	0.0	0.0	0.0	0.0	0.0	0.0	+621.7	+0.3	+621.7	+0.3	−621.7	−0.3
	38.	Sri Lanka	0.0	0.0	0.0	0.0	−2672.9	−4.0	−18,724.5	−28.3	−21,397.4	−32.3	+21,397.4	+32.3
	39.	Indonesia	0.0	0.0	0.0	0.0	+486.2	+0.0	−48,981.9	−2.6	−48,495.7	−2.5	+48,495.7	+2.5
	40.	East Timor	0.0	0.0	0.0	0.0	+52.1	+0.3	−14,218.1	−94.7	−14,166.0	−94.4	+14,166.0	+94.4

Note: Country abbreviations: U.A.E. – United Arab Emirates; Differences D2-D1 – differences between D2 and D1 (positive/negative values indicate larger/smaller surfaces of drylands in the current database compared with the initial database); in the case of percentage-based differences, certain possible minor inconsistencies of results obtained from differences D2-D1 are due to values with a single decimal point (the differences were obtained based on more detailed percentage values, with four decimal points, which were not included in this table).

[a] The states are listed in a descending order considering the maximum latitude values of northern limits.

[b] Area of Russia in relation to the Asian continent.

[c] States with disputed sovereignty.

[d] Absolute values of drylands area.

[e] Percentage of absolute drylands area in relation to the state area.

Table 7
Drylands and humid areas extent in absolute and relative values at state level in Australia and Oceania – initial drylands area/current drylands area/difference between the initial and current dryland areas.

	No.[a]	Country	Drylands/humid area (km^2/% of the country area)											
			Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands		Humid areas	
			(km^2)[b]	(%)[c]	(km^2)[b]	(%)[c]	(km^2)[b]	(%)[c]	(km^2)[b]	(%)[c]	(km^2)[b]	(%)[c]	(km^2)[b]	(%)[c]
Initial drylands (D1)	1.	Australia	0.0	0.0	3,043,862.2	39.4	3,101,073.6	40.2	598,437.8	7.8	6,743,373.6	87.4	973,152.6	12.6
	2.	Kiribati	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1018.9	100.0
	3.	PNG	0.0	0.0	0.0	0.0	607.0	0.1	4064.0	0.9	4671.0	1.0	462,189.6	99.0
	4.	New Zealand	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	269,897.6	100.0
Current drylands (D2)	1.	Australia	0.0	0.0	3,914,746.6	50.7	2,685,857.5	34.8	427,690.9	5.5	7,028,295.0	91.1	688,231.2	8.9
	2.	Kiribati	0.0	0.0	0.0	0.0	298.4	29.3	290.7	28.5	589.1	57.8	429.8	42.2
	3.	PNG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	466,860.6	100.0
	4.	New Zealand	0.0	0.0	0.0	0.0	478.5	0.2	3854.9	1.4	4333.4	1.6	265,564.2	98.4
Differences D2-D1	1.	Australia	0.0	0.0	+870,884.4	+11.3	−415,216.1	−5.4	−170,746.9	−2.2	+284,921.4	+3.7	−284,921.4	−3.7
	2.	Kiribati	0.0	0.0	0.0	0.0	+298.4	+29.3	+290.7	+28.5	+589.1	+57.8	−589.1	−57.8
	3.	PNG	0.0	0.0	0.0	0.0	−607.0	−0.1	−4064.0	−0.9	−4671.0	−1.0	+4671.0	+1.0
	4.	New Zealand	0.0	0.0	0.0	0.0	+478.5	+0.2	+3854.9	+1.4	+4333.4	+1.6	−4333.4	−1.6

Note: Country abbreviations: PNG – Papua New Guinea; Differences D2-D1 – differences between D2 and D1 (positive/negative values indicate larger/smaller surfaces of drylands in the current database compared with the initial database); in the case of percentage-based differences, certain possible minor inconsistencies of results obtained from differences D2-D1 are due to values with a single decimal point (the differences were obtained based on more detailed percentage values, with four decimal points, which were not included in this table).

[a] The states are listed in a descending order considering the maximum latitude values of northern limits.

[b] Absolute values of drylands area.

[c] Percentage of absolute drylands area in relation to the state area.

political instability. The African continent is particularly vulnerable, where a 54% increase in armed conflict incidence was estimated to occur as early as 2030 (Burke et al., 2009). In fact, this continent is already an epicentre of hunger-, poverty-, land degradation- and water scarcity-related issues (Dregne, 2002; Vörösmarty et al., 2005; Rockström and Falkenmark, 2015; Sternberg, 2016). By the end of the century, other environmental perturbations are expected as well (e.g. decreases in maize agricultural yields and in total runoff, or an upsurge of climatic conditions favorable to malaria transmission) in most of global drylands, especially against the background of a warmer world by 2 °C relative to pre-industrial levels (Huang et al., 2017b).

Asia is also a representative example in this respect, considering it is home to the world's most massive changes in terms of dryland expansion. Holding almost one third of all lands newly-affected by aridity worldwide, China is especially threatened by the intensification of certain important ecological issues such as land degradation and water scarcity. Also considering it is the world's most populous country, it is justifiable for it to receive heightened attention in terms of possible negative implications associated to the expansion of arid environments in this Asian country.

Therefore, amid the expansion of drylands and anthropogenic impact, China is already facing a massive amplification of land degradation (soil water erosion, aeolian sandy desertification) in vast regions in the north-west, north and north-east, which generally overlap the Taklamakan, Badain Jaran, Tengger and Gobi deserts (Wang et al., 2017a; Wang et al., 2017b; Zhang and Xu, 2017; Shen et al., 2018; Zhu et al., 2019). Considering the presence of land degradation in A, SA and DSH zones (which over the past decades grew in terms of area and intensity in the country's northern region, according to this study's findings), this ecological issue is similar to desertification, according to the established definitions (UNCCD, 1994). Similarly to other global regions such as Southern Europe (Prăvălie et al., 2017), desertification has become a significant environmental perturbation in these Chinese regions, as it was suggested that aeolian desertification alone is currently affecting a total area of ~1.8 mil km^2 and dozens or even hundreds of millions of people across 13 national provinces (Wang et al., 2010; Xue et al., 2013). Moreover, according to recent studies that analyzed the direct relationship between evapotranspiration and desertification, it appears that, over the next decades, this environmental issue will generally escalate in Northern China, considering the scenario of a mean global warming by 2 °C (relative to pre-industrial levels) (Ma et al., 2018), which will amplify the evapotranspiration regime and, most likely, overall aridity conditions in this region of the country.

While China is one of the countries holding the largest fresh water resources, territorial discrepancies, reflected in a more arid northern region (with much lower water availability compared to the wetter south – only 18% of the national fresh water volume) (Piao et al., 2010), are a factor that makes the country particularly vulnerable to the enhancement of aridity conditions. In fact, there are already clear signs that point to a persistent decline of water resources in the north, e.g. the observed decreases in the annual runoff of the Yellow River (attributed to climate change, including drier conditions confirmed by our study, but also to the overexploitation of water for irrigation, industry or domestic usage) (Zhang et al., 2009). In the long term, even the rich water resources in Western and Southwestern China can be endangered by further intensifying climate warming and aridity (already prominent in this region as well), first and foremost as a result of glacier melt (important source that contributes to river runoff) – it was suggested that over 80% of western China's glaciers are currently retreating and that by 2100 as much as 67% of the country's glacial area may disappear (Li et al., 2010; Piao et al., 2010). Therefore, a drier future could be largely responsible for the major decline in water resources projected for the 21st century in this Asian country and in other countries of the world.

5. Conclusions

The expansion of global arid environments reflects a drier planet than previously acknowledged. Our new results, based on the first diachronic analysis of two important global aridity databases (as opposed to other previous analyses that investigated the status of the new AI and compared it briefly to that of the previous AI, only globally, without any detailed continental and national analyses), confirmed massive overall dryland expansions in the past decades worldwide. Our statistical results highlighted a net maximum expansion of arid environments in Asia, where it seems that China alone totaled almost one third of the lands newly-subjected to aridity globally, or almost half the lands, if assessing it alongside Asian Russia. Against the background of increasingly widespread and intense aridity conditions, we issued a warning regarding the

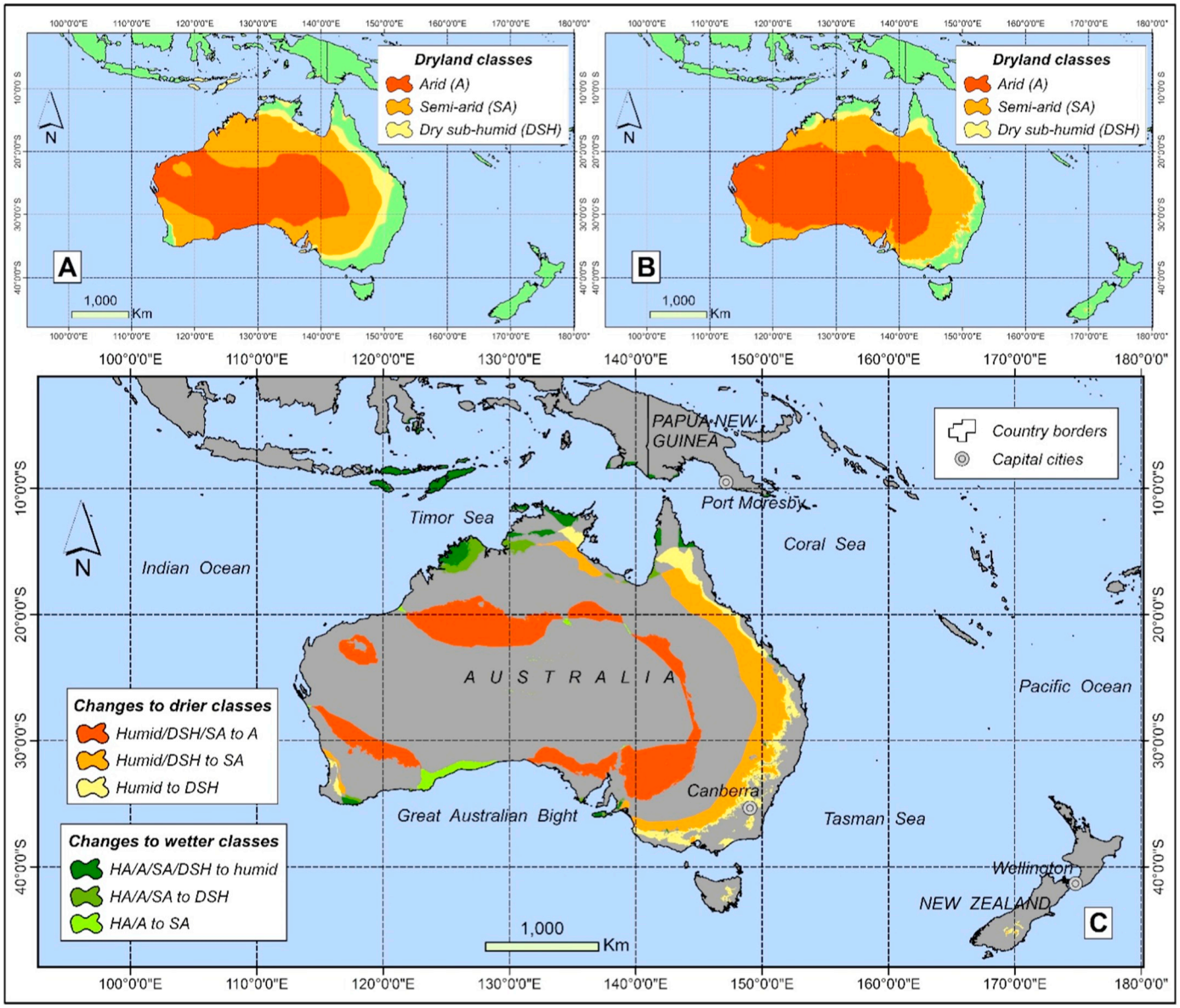

Fig. 7. Previous estimates (a) of the Australia and Oceania drylands (spatial data processed after Middleton and Thomas, 1997) versus current estimates (b), based on a new global AI database (data processed after Trabucco and Zomer, 2009) and spatial differences between these two databases (c). Note: in maps a and b, light green reveals humid areas, while in map c gray shows areas without changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environmental threats associated with a more arid world, both at low and middle (land degradation, water scarcity and others), and high (positive warming feedbacks related to destabilization of the snow cover, permafrost, peatlands and boreal forests) latitudes.

We therefore want to draw attention to the need for further studies on the global expansion of arid environments, for instance in terms of the concrete causes for changes in precipitation and evapotranspiration and, implicitly, in aridity conditions. Although this particular issue was not explored in the current paper, we encourage further studies to analyze, in concrete terms, the climatic (the obvious example of climate warming) or even non-climatic (e.g. possible regional land use/land cover changes that can influence PET values and implicitly the P/PET ratio) driving forces of dryland expansion. These research trajectories would help gain a better understanding of the mechanisms governing arid environment dynamics, and would contribute to a more efficient prioritization of the measures needed to fight the multiple negative effects associated to land degradation, desertification and to other environmental perturbations.

In this context, we urge the United Nations (UN) to intensify efforts to fight land degradation and improve livelihoods in drylands, via UNCCD (United Nations Convention to Combat Desertification), UNEP (United Nations Environment Programme) or UNFCCC (United Nations Framework Convention on Climate Change). Additionally, enhanced research, monitoring and forecasting initiatives that analyze arid environments and address their climate warming feedbacks in high-latitude regions are essential. UN actions must be bigger, better and faster, considering that more aggressive expansion of drylands is expected *vis a vis* areas that will become wetter (Feng and Fu, 2013; Huang et al., 2016), in the context of imminent climate warming of this century.

We identify the necessity of a UN holistic vision when addressing dryland environments. Engagement can aim to stabilize these lands in a warmer future through sustainable economic growth, reduce poverty in developing countries and improve environmental stewardship. There are concrete ways to meet these objectives, such as the use of renewable energy, particularly solar energy, which is the most abundant in dryland systems (Prăvălie et al., 2019). For instance, it was suggested that

the same amount of energy produced worldwide today would be generated if only 4% of global deserts were to be covered with solar power systems (Kurokawa, 2007). However, we believe the success and widespread use of sustainable energy will largely depend on investments made the UN, through the UNDP (United Nations Development Programme) or by the World Bank, which will complement and reinforce similar national initiatives around the world. In an era of expanding drylands direct human action is needed to counter the potential devastating implications for our drying planet.

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